DEVELOPMENT OF A DESIGN FOR MANUFACTURE CONCURRENT ENGINEERING SYSTEM

by

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ABSTRACT

Keywords: Concurrent Engineering, Teamwork, CAD/CAM, Feature Recognition, Constraint Knowledge-based System, Process Planning, Object-oriented Programming, Data sharing.

The major aim of this research work was to develop an Intelligent Design Environment for Supporting Concurrent Product and Process Design. The system was designed in such a way to enable users to monitor the design as it progresses and to improve quality and reduce the cost. It has also the facility to examine if the designed part can be manufactured in house with the available manufacturing facilities and provides feedback related to machining concerns that may arise.

The development process was passed through three fundamental stages to accomplish the proposed paradigm. These stages were: first, developing a technique for automated feature recognition from a solid modeller, secondly, linking a Knowledge-based with a Solid Modelling and a Process Planning System and finally, building a Constraint Knowledge-based System which could provide feedback connected with manufacturability concerns such as process limits or design inconsistencies. It also gives a predictable machining cost estimation and continuous feedback to designers about possible manufacturing issues or requirements as the design proceeds.

Developing an approach for feature recognition was substantial for a number of reasons; most solid modellers available today represent part geometry in terms of low-level geometric and topological entities such as faces, loops, edges, surfaces, curves and points. These modellers do not provide higher level abstractions of a part that relate directly to certain design functionalities or manufacturing characteristics. Therefore, these systems cannot be used directly to derive applications such as design analysis, machining cost estimation or process planning which are the core of this research. A solid modeller package (Pro/Engineer) has been enhanced to co-operatively assist designers in creating new applications that can be directly integrated into the CAD System (Pro/Engineer) environment and extracting the necessary topological and geometrical information from the solid modeller

during the design stage. Pro/Develop, the programmatic interface of the CAD system database, in addition to bespoke software written for the UNIX environment were implemented to achieve this goal. A user interface was set-up to enable users to interact with the system easily and efficiently. The interface includes facilities to create features such as holes, fillets, slots, rounds, and drafts.

Integrating the Knowledge-Based System with the CAD solid modeller was vital for facilitating the data transfer process between the systems. It also allows design for manufacturing and cost analysis to be automated and relieving designers of any additional tasks that otherwise would be created. A number of problems were encountered during constructing the connection between the systems. For instance, KEE does not provide external communication capabilities, but allows complete access to Lucid's Common Lisp language which in turn supports a foreign language interface. Meanwhile, the KBS was developed using Common Lisp language programs to interact with the CAD package directly.

The KBS was constructed and designed to capture information about model features, such as shape and geometry, then calculates the cost of the features at each stage of the design. Extensive knowledge concerning manufacturing facilities and model features were represented in a hierarchy tree inside the KBS. Consequently the designer is able to get information about these facets at any stage during the product-life cycle development.

This work is part of the current research plan for developing a generic system suitable for various manufacturing practices based on a Concurrent Engineering Strategy.

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Thought thousands of miles away, the good wishes and best regards to my parents, brothers especially Dr Mohammed Abdalla and sisters for their constant source of encouragement and kindness.

Hassan Abdalla

This humble work is dedicated

to my parents who were my

first teacher.

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NOMENCLATURE

Symbol	Definition
AEX	Assembly Expert
AFR	Automated Feature Recognition.
B-Rep	Boundary Representation Scheme
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CALS	Continuous Acquisition and Life-cycle Support
CE	Concurrent Engineering
CEDE	Concurrent Engineering Design Environment
CIM	Computer Integrated Manufacturing
CONSENSE	Concurrent/Simultaneous Engineering System
CONSYST	Constraint Management System
CSG	Constructive Solid Geometry
DCA	Design Compatibility Analysis
DFA	Design for Assembly
DFM	Design for Manufacturability
FRS	Feature Recognition System
GCE	Global Concurrent Engineering
IT	Information Technology
KBS	Knowledge Based System
KEE	Knowledge Engineering Environment
PACE	A Process Planning and Concurrent Engineering System
PCB	Printed Circuit Board
PPS	Process Planning System
STEM	Shaped Tube Electronic Machining
STEP	Standard for the Exchange of product Model Data
UDF	User Defined Features

RACE	Readiness Assessment for Concurrent Engineering
OOPM	Object Oriented Product Model
OOP	Object Oriented Paradigm

CHAPTER 1

1.1 BACKGROUND

Today, within such a distributed product development environment, fast changing and highly competitive economies are forcing industries world-wide to seriously consider various ways to reduce product development time and cost. One of the best practices to produce a product at high quality and low cost with existing manufacturing facilities is Concurrent Engineering (CE). Concurrent Engineering addresses the issue of developing a product that meets market requirements and expectation by concurrently taking into consideration different product life-cycle concerns during the product development process. It also involves design, materials, manufacturing processes and cost, taking into account later-stage considerations such as testability, serviceability, quality, and reliability. This is very important to the manufacturing industry because after a product has been designed and passed from the design stage to the manufacturing stage, it is then too late to make significant changes to reduce life-cycle expenditures. When only functional, structural, and machining life-concerns are considered, Concurrent Engineering or Design for Manufacturability entails simultaneous product and process design. To establish this requires that satisfactory manufacturing information should be brought to bear on design decisions at the beginning of the design stages.

Such concurrent engineering environment requires parallel interactive activities and co-operative teams. However, the full realisation of such an approach in a product development practice is a very difficult task for the following reasons; firstly, lack of a comprehensive model clearly describing the decision activities in simultaneous product and process design; secondly, lack of sufficient computer-based tools capable of supporting co-operative decision making activities.

Over the last few years considerable research work has been directed towards investigating the techniques and tools needed for implementing Concurrent Engineering strategy. Most of these studies have not addressed or developed an efficient methodology to help designers conduct the discipline. A key aspect of this methodology is to assure that components are manufacturable for the lowest possible cost in specially designed manufacturing facilities such as manufacturing cells. However, the implementation of CE strategy has been shown to be a non-trivial task inherent difficulties have to be overcome before the full benefits can be accomplished. Since designers need to be equipped with effective tools, which act as a formal feedback route from the manufacturing phases. Tools applicable at the conceptual stage need complements at the detailed design stage, co-operative Knowledge-based Tools can fulfil this role. A paradigm that can be used for achieving some of the CE goals has been developed in this research.

It can be summarised that CE aims at considering all elements of product life-cycle from conception through disposal including quality, cost, schedule and user requirements. The benefits of implementing the concept of concurrent product and process design are reduction of cost; improvement of quality; elimination of waste; reduction in lead time for product delivery and continuous product improvement.

1.2 RESEARCH AIMS AND OBJECTIVES

The main aim of this research was to develop a Concurrent Engineering Design Environment which enables designers with limited knowledge of manufacturing methods to generate cost effective designs at the detailed stage. The following objectives were carried out to establish the system:

- Development of a technique for automated feature recognition from a solid modeller.

- Development of a paradigm for integrating a CAD system with a Knowledge-based as well as a Process Planning System, so a continuous flow of information can be transferred between the systems. This information can be used for several applications such as cost estimation, processes planning, design analysis and optimisation.

- Development of statistical correlations for feature based cost generators for families of manufacturing processes and to develop a Knowledge-based System which chains cost dependent rules in order to give estimates and advice on reduced cost alternatives.

- Development of search strategy which analyse the data structure of an unconstrained solid model with the intention of identifying features in order to generate associated costs.

1.3 ORGANISATION OF THIS THESIS

Chapter (2) presents a literature survey of research work in various areas relevant to this research. The survey started with the area of Concurrent Engineering in terms of its benefits, difficulties associated with implementing its concept, different approaches for implementing CE, such as team work, and rule-based systems. The survey covered other interesting areas including Design for Manufacturability, Design for Assembly, Feature-based Modelling, Computer-aided Design, Computer-aided Process Planning, Design to Cost, Part Representation Schemes and Knowledge Based Systems in CAD Environments. Chapter (3) describes the structure and characteristics of the proposed Concurrent Engineering Design environment.

A technique for Automated Recognition of form features from a 3D Solid Model is presented in details in Chapter (4). This chapter includes also some information concerning form features in terms of its terminology and definitions. Chapter (5) illustrates the Knowledge-based System Construction steps and the Interprocess Communication with the Solid Modeller as well as the process planning system.

Chapter (6) describes an intelligent interactive CAD & KB system which has a mechanism for constraint checking in the design process. Since most of the design constraints arise from other engineering aspects, the system is based on the concept of concurrent engineering. The system integrates a geometric modeller and a reasoning system which contains production rules. The geometric modeller is used for representing the shape of the object and for extracting information for constraint checking, cost estimation, process planning, and other applications. Constraints imposed by structural functionality of the design, requirements from other domains, such as manufacturing, was also taken into consideration. The reasoning system (production rules) is used for representing the constraint checking and data updating procedures, and can be executed as required.

Chapter (7) describes the implementation of the system within a case study. It illustrates the proposed model for controlling the data exchange throughout the product life-cycle. Finally, discussion, conclusions, important observations and recommendations for future work are discussed in Chapter (8).

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

Key factors in answering the survival of industries and/or companies is efficient integration of equipment, techniques and strategies which can be used with an effective organisational structure enabling the production of high quality, well-designed, products with high customer acceptance at competitive prices and in less time. The product design phase has been recognised as being imperative for success and consequently significant awareness is being drawn to it. Little benefits can be brought from the implementation of advanced Computer Integrated Manufacturing (CIM) technologies unless product design lends itself to the overall system utilising all available and relevant technologies. Many workers have commented on the significance of product design. Young et al (1992) have shown that upwards of 70% of a product's cost is determined by decisions made during the design stage. Decisions made at this stage have significant impact on the final product cost and time to market. It is estimated that 40% of all quality problems can be traced to poor design, Dixon and Duffey (1988). Suh (1990) believes that as much as 70-80% of manufacturing productivity can be determined at the design stage. Gatenby et al (1990) estimate that an even higher percentage (from 80 to 90%) of total life-cycle cost of a product is determined during the design stage. Manufacturers have to contend with the removal of traditional trade barriers and have to learn to come to terms with the demand for new products which have to be brought to the market place in even shorter times in order to remain profitable.

A review of research work in the areas of Concurrent/Simultaneous Engineering (CE), Design for Manufacturability, Design to Cost, and Design for Assembly is presented in the following sections. The area of CE is presented in section 2.2. Literature in the areas of Design for Manufacturability, Design for Assembly, Part Representation, Feature-based Modelling and Computer Aided Design, is reviewed in sections 2.3, 2.4, 2.5. 2.6 and 2.7 respectively. The main intention in reviewing literature in these areas is to study the extent to which previous researchers have addressed any of the relevant aspects of the CE and Design to Cost concepts. Work in the areas of Feature-based Design by Constraints, Computer Aided Process Planning and Knowledge-Based Systems in a CAD Environment is summarised in sections 2.8, 2.9 and 2.10. A brief review of using Knowledge-Based Systems for cost estimating is presented in section 2.11. Finally a summary of this literature survey is given in section 2.12.

2.2 CONCURRENT ENGINEERING

Concurrent engineering is a product development methodology which intends to reduce time-to-market, whilst reducing product cost, and increasing customer satisfaction. It has been recognised that the gap between understanding the principles and culture involved, and in getting a programme up and running successfully remains significant, Abdalla (1994a) and Laming (1994). A frequently cited definition of concurrent engineering was proposed by the US Institute for Defence Analysis, Winner et al (1988) *Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements.* In the context of product design, CE has been recognised as a viable approach in which the simultaneous design of a product and all its related processes in a manufacturing system are taken into consideration, ensuring required matching of a product's structural, functional requirements and the associated manufacturing implications. Processes influencing product design usually include market analysis, materials procurement, product cost estimation, machining, assembly, inspection as well as the later phases of the product's life-cycle such as service and maintenance, and disposal. This means that the different functions within a company should work together without the execution of difficulty or problems even if they are located in different geographical locations. The result of the design should be the same regardless where it has been designed. CE philosophy provides an environment that leads to developing a product in more systematic way.

The concept of concurrent Engineering has shown its necessity because of the major problems facing industry today typically: -

- Lack of a communication view, the goals and interfaces.
- Frequent redesign and changes during the product process.
- Designers spend too much time from product idea to product decision.
- Customers are not adequately involved in new product initiation.
- Marketability approvals are not systematic and wide enough.
- Systematic or sequential communication between the separate functions and organisational levels.

Concurrent or Simultaneous Engineering (CE) has been widely recognised as a method by which companies can overcome the above problems and improve performance, particularly in terms of cost, better communication and shorter time to market, Neto (1989). In truth, CE is not a new strategy. Several years ago, progressive management recognised the need for cross-functional communication and simultaneous tasking between design, development, production and marketing departments to reduce overall product development time and to design products which more closely matched customer's requirements. However, evidence suggests that industry falls short in its understanding of CE as a design management tool and how attention to design and management of the design process determine a company's competitive and commercial position, Abdalla (1994b). A Design Council survey carried out by Nichols et al (1993) found that only 16 % of engineering companies claim to have adopted CE as the normal way of conducting product development, while 34 % had little or no understanding of CE. Companies that do use CE report shorter development times, lower costs and improved quality. One of the major impediments to the wider adoption of CE is the culture shift that it demands. People who have not worked together previously now have to do so on a day to day basis. They have to understand the functions of other people and how they affect company performance. Successful implementation of the CE approach to product development does not come easily, management must be prepared to persist and learn from their own mistakes and take a long term view, Abdalla (1994c). The benefits of CE can be summarised as follows: products match needs, shorter time to market, greater quality control, reduced unit costs, easier and cheaper to manufacture, higher quality, increased customer acceptance, and reduced risk of failure. Research work has been recently directed towards developing methodologies and tools for supporting CE strategy.

CE approach advocates a parallel design effort with an objective to ensure that serious problems would not occur at the downstream stage. A number of approaches for realising the essence of concurrent engineering have been proposed recently by different authors. For instance, Eversheim (1990) illustrated the major elements that have to be considered to practice CE, as shown in figure (2.1).

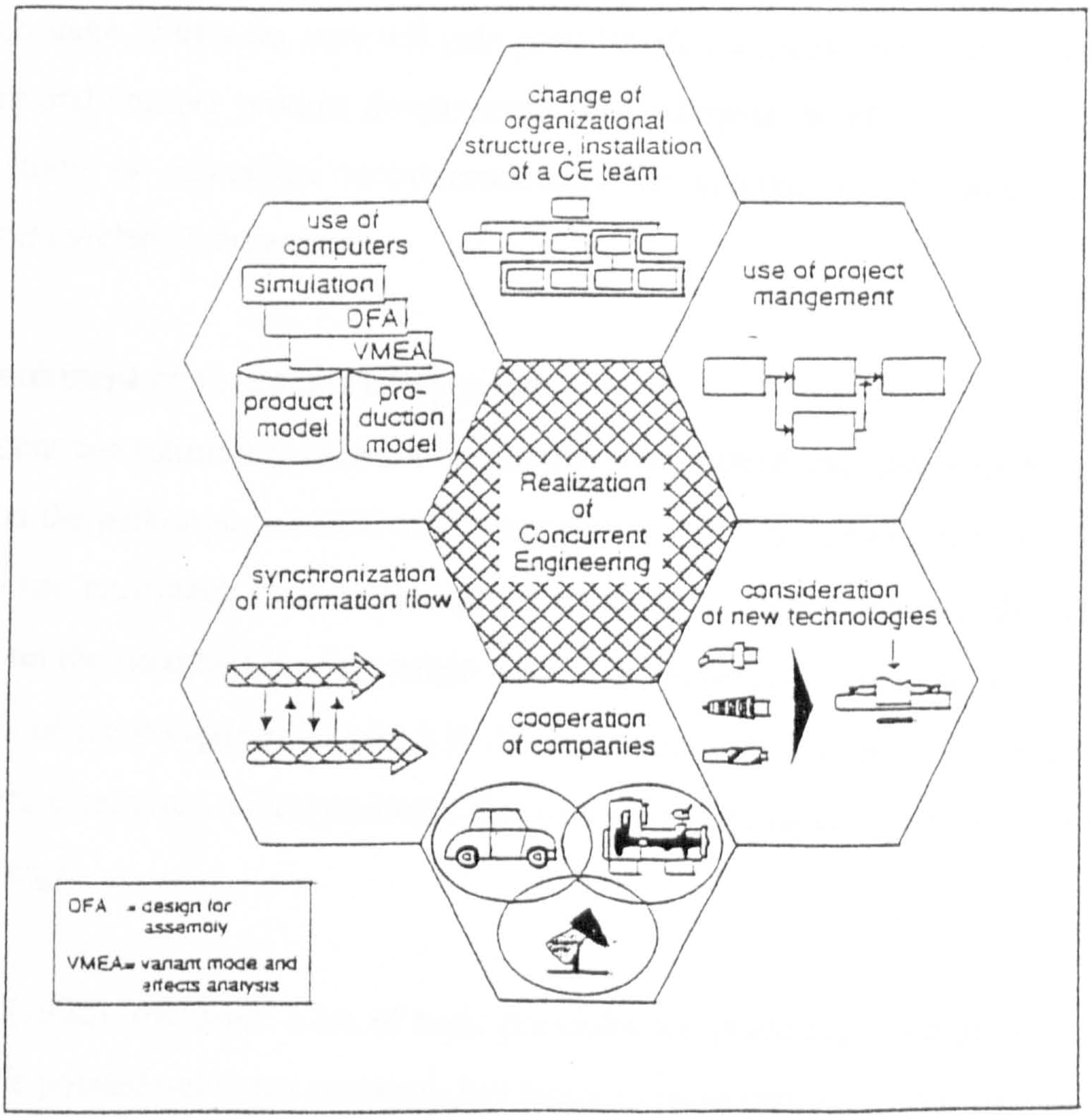


Figure (2.1) An Approach for Concurrent Engineering

2.2.1 Guide lines for implementing a Concurrent Engineering strategy

A set of guide lines for a good CE practice were drawn from a multinational collaborative project for global manufacturing, Abdalla (1994c). Basically, any company wishing to embark on CE needs a logical analysis of what issues should be addressed, in what order and by what tools and techniques. They need a step-by-step approach to help them systematically improve operations and understand the impact of their decisions on other parts of the business. They need to highlight potential pitfalls, so they can understand, what might go wrong, why, and how it can be prevented. The results of a benchmarking exercise showed that over 50% of the participants identified cultural or communication issues, as major obstacles to progress in a global market. Also for most companies' their experience in Global Concurrent Engineering (GCE) was focused on learning how to break down barriers between departments. Companies should invest enough time on getting all aspects of the product, process, customer requirements and support sorted out as early as possible during the design stage. If they do, they will gain great benefits, such as fewer engineering changes, and faster and cheaper product development. The following points were considered in the current study as substantial recommendations for creating a Concurrent Engineering environment within an organisation.

- **Commitment from senior management**

Management commitment provides a conductive environment and senior managers should understand the philosophy of GCE and its benefits in order to be more dedicated. From this base they can encourage their employees for engendering implementation the strategy and emphasis on the necessity for the change when it is required, to meet market requirements. Over 44% of the companies involved in the benchmarking admitted that management and resistance to change are critical problems that may have to be faced during implementation of GCE strategy.

Raymond (1992) discussed a set of basic principles for practising Concurrent Engineering strategy. He pointed out that a necessary key factor to make process engineering successful is executive leadership with real vision. Consistent management commitment could raise the productivity and quality of a product by ten times.

- **Employee Commitment**

Employees have an image of their company which differentiates it fundamentally from others and makes it a unique and special place. Their commitment increase the effectiveness of team work and ensures successful implementation, sustainability can be ensured by employee participation. Emphasise on team-work, involving all employees at every level, based on a flattened management hierarchy is essential. Companies should challenge all current thoughts and beliefs relating to all aspects of the business operation and stress suggestion schemes which involve contribution possibilities for all employees.

- **Clear Strategy**

Organisation efforts and strategy should be clear, moving in a common direction towards achievement of on-going company wide progress. Formulate the company activities towards continuous process improvement. Develop not only a vision for the future but also the necessary steps towards achieving it.

- **Teamwork**

An essential component of GCE is teamwork. The quality of collaboration within the teams, co-operation across different teams, operating units and divisions, are important factors for a company's success. A design team approach requires early and frequent interaction between design and the other life-cycle functions. Team members consisting of designers and individuals from all other related functional areas including finance, marketing, design, manufacturing, simulation, testing, production planning, and quality, ie. representatives covering the entire product life cycle and its associated cost implications for the business are brought together for their ability to contribute to the design of the product and processes by early identification of potential problems and timely initiations of actions to avoid a series of costly reworks. Those teams should share responsibility and each team should have a complete responsibility for the end product it delivers. Team members should also share responsibility for attaining the team's goals and objectives as well as the overall direction and achievement of the task. It is through team working that cross fertilisation occurs ensuring the success of the project, Abdalla et al (1994d). While team approaches appear to have been effective in a number of instances, some difficulties remain unsolved. First, group decision making, especially for creative tasks, can be difficult and the effective management of the team can be demanding, Harfmann (1987). Second, the team members may not have detailed knowledge of all aspects of the life-cycle of the product and the design may therefore be biased towards particular considerations. Third, the cost of maintaining a team, and the difficulties of assembling the team, may make it uneconomic or onerous to use. This specially true for small or medium volume products.

Constantine (1993) introduced some of the key features of structured group techniques for applications and software development. He also described briefly a number of small groups methods that have been used effectively for consensus engineering or concurrent engineering. He indicated that effective and efficient performance of project teams can be enhanced through the use of specific group problem-solving and decision making techniques, especially ones tailored to the issues and tasks of object-oriented software development.

- **Team building skills**

Organisations should invest and concentrate on team building skills through establishing well defined long term training schemes. Survey results have shown that lack of awareness of GCE approach is one of the major barriers towards implementing its philosophy. Several companies and organisation stressed the lack of information and poor definition of GCE as impediments to pursuant their people to adopt the concept. Team members should not experience culture shock as they begin work in an environment, where it is illegitimate to challenge working practices, procedures and corporate norms. People are the most valuable resource, therefore, it is important to provide them with better communication and clear guidance, as to what is expected from them whilst recognising the risks involved and the changes that are likely to occur. Consequently, the important issue to reduce risks is to plan accordingly, and to continuously strive to improve future performance.

- **Communication and Functions Co-location**

Communication is vital to any change, it increases the efficiency of the change process. How the teams communicate is very important for making the right decision quickly during the product development session. Some of the organisations collocate their team members in order to achieve better communication, others use a combination of both face to face meetings, information systems to facilitate better communication, understanding, and making quicker decision at an early stage during the product development process.

- **Technology Enables**

Information Technology (IT) tools such as engineering database management systems assist in getting information to the right people at the right time with minimum effort. An IT infrastructure is needed which can support the flow of information between the people involved in all aspects of the business. Members of the team need effective and efficient ways of transferring data/drawings and also communicating. The IT system employed should have the ability to hold all information about the product and maintain the integrity of data, integration of tools, techniques and teams can be co-ordinated through a paper based, or computer based formal project management system. One of the essential and basic principles of CE is the concurrency of activities which can contribute radically to productivity, cycle time reduction, quality, and reduce product development times. The use of technology to enable this to occur is essential, technology facilitates easy access to information through either local area networks or wider area networks; eg materials information should be available through the company database or through more remote databases accessed via modem anywhere in the world.

- **Data sharing and standardisation**

The effective use of concurrent engineering practice requires access to an organisation of knowledge accumulated over time, processes, and customers. Separate knowledge resources have to be shared and co-ordinated over space and time. Subrahmanian et al (1993) have addressed the nature of communication in design, especially across disciplines, and the support system that could facilitate better communication. Lalande (1992) examined the issues involved in the communication between companies of CAD/CAM/CAE data.

The use of the international standard for the exchange of a product model data (STEP) is important for facilitating data sharing. All teams should be able to get access and share data throughout the organisation very easily. The preliminary step towards facilitating data sharing is data integration (see figure 2.2), centralisation, a network system, and data standard. Cross-functional communication and simultaneous tasking between design, development, production and marketing departments are necessary to reduce overall product development time and to design a product which more closely matches customer requirements.

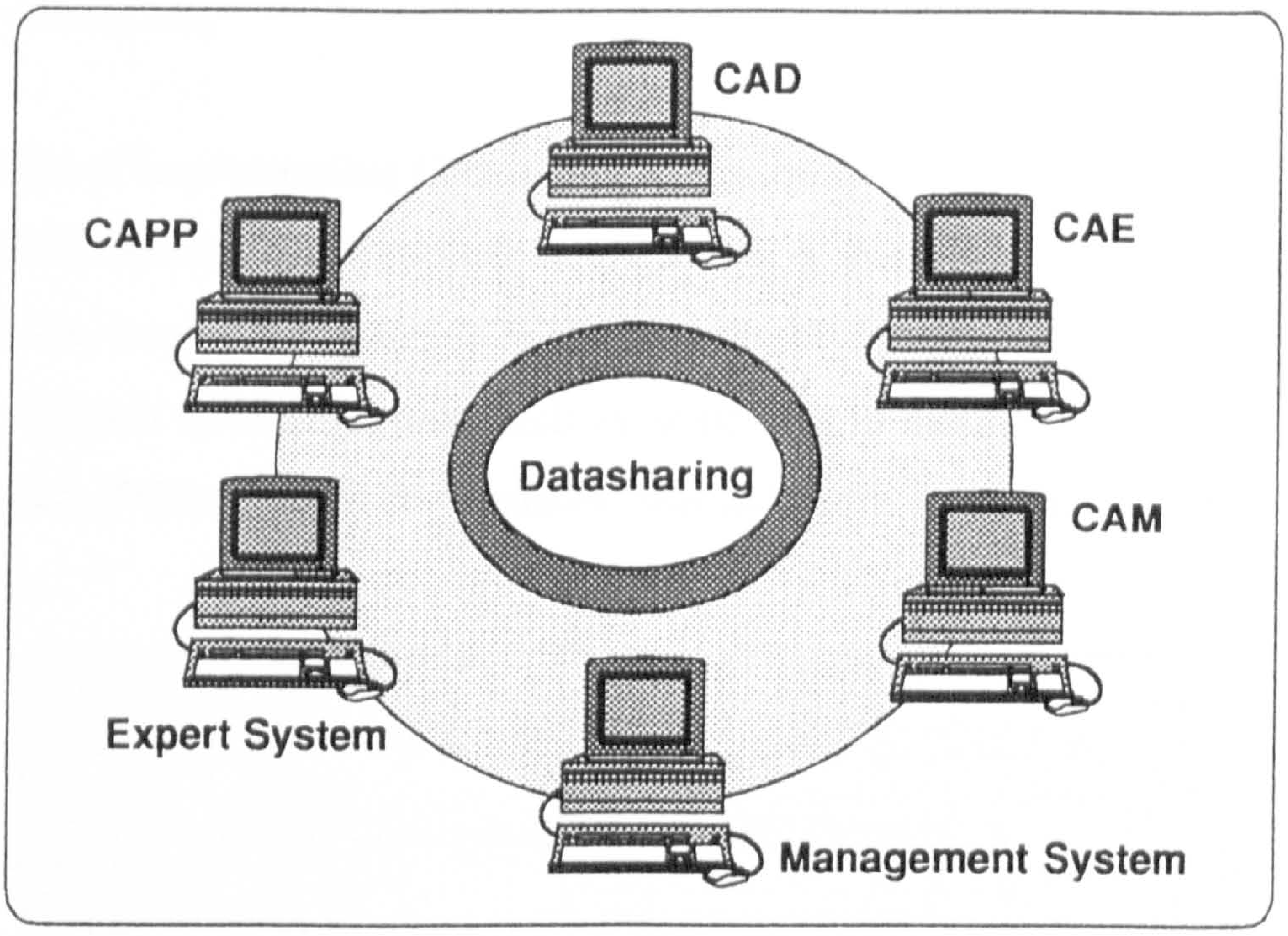


Figure (2.2) Data Sharing and Integration In a CE Environment

O'Brien (1992) has discussed different approaches for some of the companies that are attempting to implement a concurrent engineering strategy. He highlights the need for "better information systems, software systems and decision support tools to support concurrent engineering activities". A number of examples of various concurrent engineering approaches and enabling technologies were demonstrated.

The requirements of the amplification of concurrent engineering for organisational knowledge and the distribution of this knowledge between people and technical systems were outlined by Siemieniuch and Sinclair (1993). They emphasise the importance of standards, including some that refer to ergonomics issues.

The benchmarking exercise, Abdalla et al (1994e) shows that lack of product information (historical data), and information recording and retrieval in terms of job costing, cost of material, man power, processes, problems etc, for previous projects and products should be available for the product developers in an easy access at any time. If this happened mistakes made previously can be predicted and avoided, IT tools can be useful for that purpose. Analysing the information and decision consequences, should be assessed, and the impact should be pointed out.

2.2.2 Benefits of Implementing Concurrent Engineering

Significant CE benefits were reported as a result of a world wide benchmarking survey, Abdalla (1994c) as shown in figure (2.3), the most notable benefit was shorter time to market (70%). In addition to other benefits such as: improving communication (59%); improved product quality (56%); reduced development costs and better management (33%);

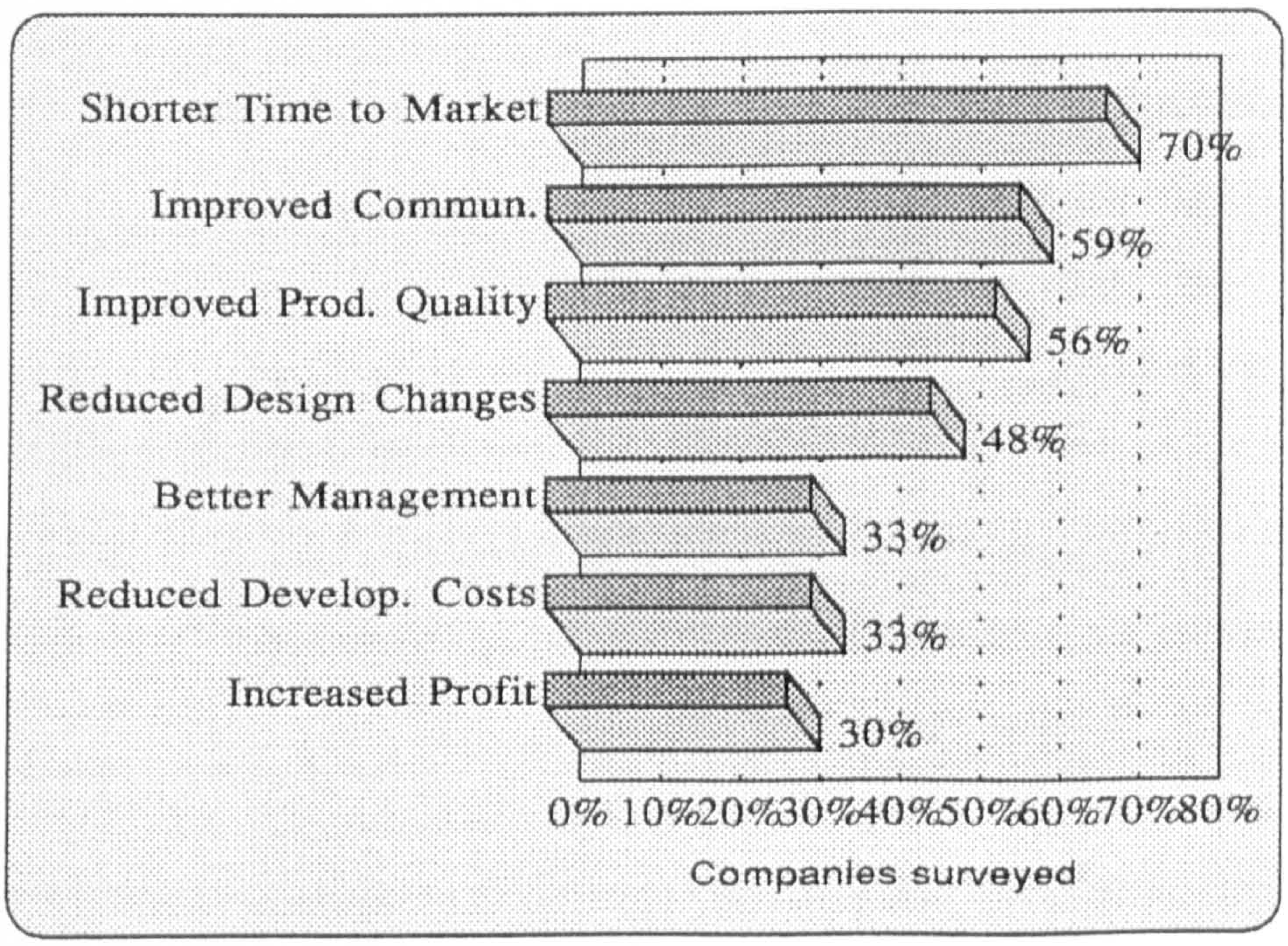


Figure (2.3) Benefits of Implementing Concurrent Engineering

reduced design change (48%) which means shorter ramp-up time and improving the company's competitiveness. The Design Council Survey, Nichols et al (1993) has also shown that late design changes can seriously affect development costs, as they are probably the most expensive to implement. It showed that between 30% to 50% of the companies were suffering from the high level of engineering rework. These benefits are very much interrelated and lead to other achievements such as increasing market share, and customer satisfaction. Other major aspects and challenges of successful concurrent engineering programmes were discussed by Goldense (1992).

2.2.3 Difficulties Associated with Performing Concurrent Engineering

The fact that CE is not performed well is due primarily to three main sources of difficulties: the characteristics of design process, the volume and variety of life-cycle knowledge, and the separation of life-cycle functions, Evans (1988). Design is thought to involve the separation of the design problems into stages namely conceptual design, detailed design, and analysis and evaluation. These stages are then carried out by iteratively solving each sub-problem within a stage until the overall design is thought to be adequate. This division of design problem can result in 'sub-optimisation' where the designer concentrates on narrow issues while ignoring the overall CE problem. The second source of difficulty stems from the fact that the knowledge required is voluminous since it will include design, manufacturing, manufacturing control, testing, servicing and redesign. The required knowledge will also have a large degree of variety, including both qualitative and quantitative knowledge. As a result, relatively narrow functional domains of knowledge are developed, ignoring the rest of the life-cycle knowledge, Swift (1989).

The third source of difficulty associated with CE is that different life-cycle functions are often separated by being the responsibility of different departments in an organisation. Communication barriers within such an organisation will mean that knowledge about life-cycle factors is only infrequently passed back to the designer. These sources of difficulties will result in designers frequently defer considering life-cycle requirements until late in the design process or abdicate responsibility to the relevant life-cycle function within the company, Evans (1988). Other difficulties were reported from the feasibility study of the Global Concurrent Engineering project as shown in figure (2.4), Abdalla (1994a).

The Concurrent Engineering Research Centre (CERC) has developed a model, a measurement tool, and a methodology is called RACE (Readiness Assessment for Concurrent Engineering) to assist CE implementors in identifying the barriers and prioritising implementation actions, Karandikar et al (1993). The major barriers identified were cultural, organisational, and technological in nature.

2.2.4 Approaches to Concurrent Engineering Implementation

There are a number of techniques and systems that support CE by advising designers on aspects that reduce life-cycle problems. These include the use of design teams, manufacturing simulation and process planning, the use of expert systems, and computer-based CE environment.

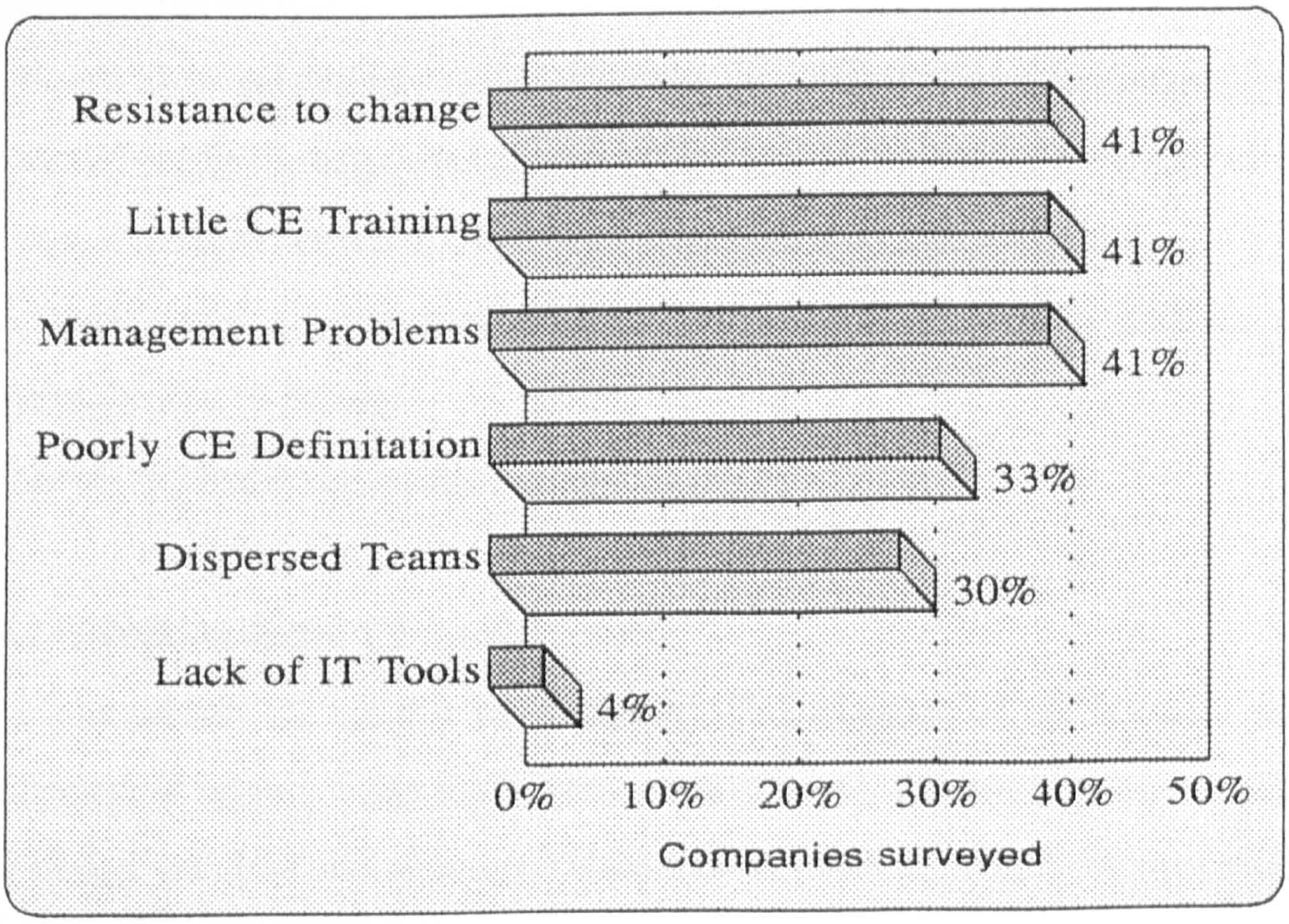


Figure (2.4) Difficulties Encountered During Implementing Concurrent Engineering

2.2.4.1 Rule-based Expert Systems

There are relatively few computerised systems that support CE. The existing ones are mainly rule-based expert systems. The advantages of rule-based systems are that they are relatively effective and simple to use. However, most are applicable to very small application areas and have problems in being expanded to handle wider application areas. Furthermore, a prime requirement of supporting CE is the ability to represent the mutually constraining influences that different aspects of a product's life-cycle exert on each other. This is not easily achieved using rule-based systems. However, this review has shown that work done thus far on supporting CE is limited. As has been indicated, design teams that possess the requisite life-cycle information can produce good results. In view of the shortcomings that arise with design teams, the use of a computerised support tools to bring up-to-date life-cycle information to the designer in a readily usable form has been given immense attention. This support tool will, in effect, emulate a good design team by suggesting changes that will improve the design from the life-cycle perspective. Overall, the following are the principal requirements of a computerised system to support CE.

- it should be flexible enough to allow the design problem to be approached from a variety of viewpoints
- it should allow the designer to design despite the absence of complete information
- it should handle the large volume, variety, and interdependence of life-cycle information
- it should readily interface to database management and CAD systems
- it should have a good user interface and be able to explain itself in a manner comprehensive to humans
- it should support design audits

2.2.4.2 Computer-based CE Environment

One of the primary factors that has facilitated the application of CE in recent years is the development of system design tools. These tools allow for the simultaneous consideration of many design variables and structured trade-offs of multiple, sometimes opposing, product characteristics. In many cases, computer automation has led to new methods of considering many aspects of design, production and support, thus improving overall product utility and avoiding costly delays and redesign in transferring technology from development to technology. The underlying prerequisite to the computer-based approach is systematically to acquire, represent, integrate, and co-ordinate the requisite CE knowledge with which computers can perform the required analysis. A number of computer-aided design (CAD) tools are also required during the design stage to examine the influence of the design on the product's life-cycle. Consequently, the expectation is to see an integrated design environment in which all the CAD tools interact and cooperate to find a globally optimised or compromised design. Figure (2.5) shows a conceptual model of the approach proposed by Jo et al (1993). In the figure, the outer layer of the 'concurrent engineering wheel', product models are advanced which can provide designers with the capability to invoke any tools in the layer to evaluate or optimise their designs. The core of the wheel is the control logic which involves the steering of various CAD tools to provide a variety of services, helping to find a globally satisfied design. It must be emphasised that it is at the core of the wheel for which scientific theories of the design process are badly needed. Between the outer layer and the core is the functional layer that comprises various life-cycle analysis tools. Other aspects of a product's life-cycle which may be inserted into this layer include market analysis, disposability, packing/shipping, social impact, and so on.

Concurrent Engineering is a philosophy that integrates all the product related activities and focuses on customer requirements, process definition and process optimisation. In such CE

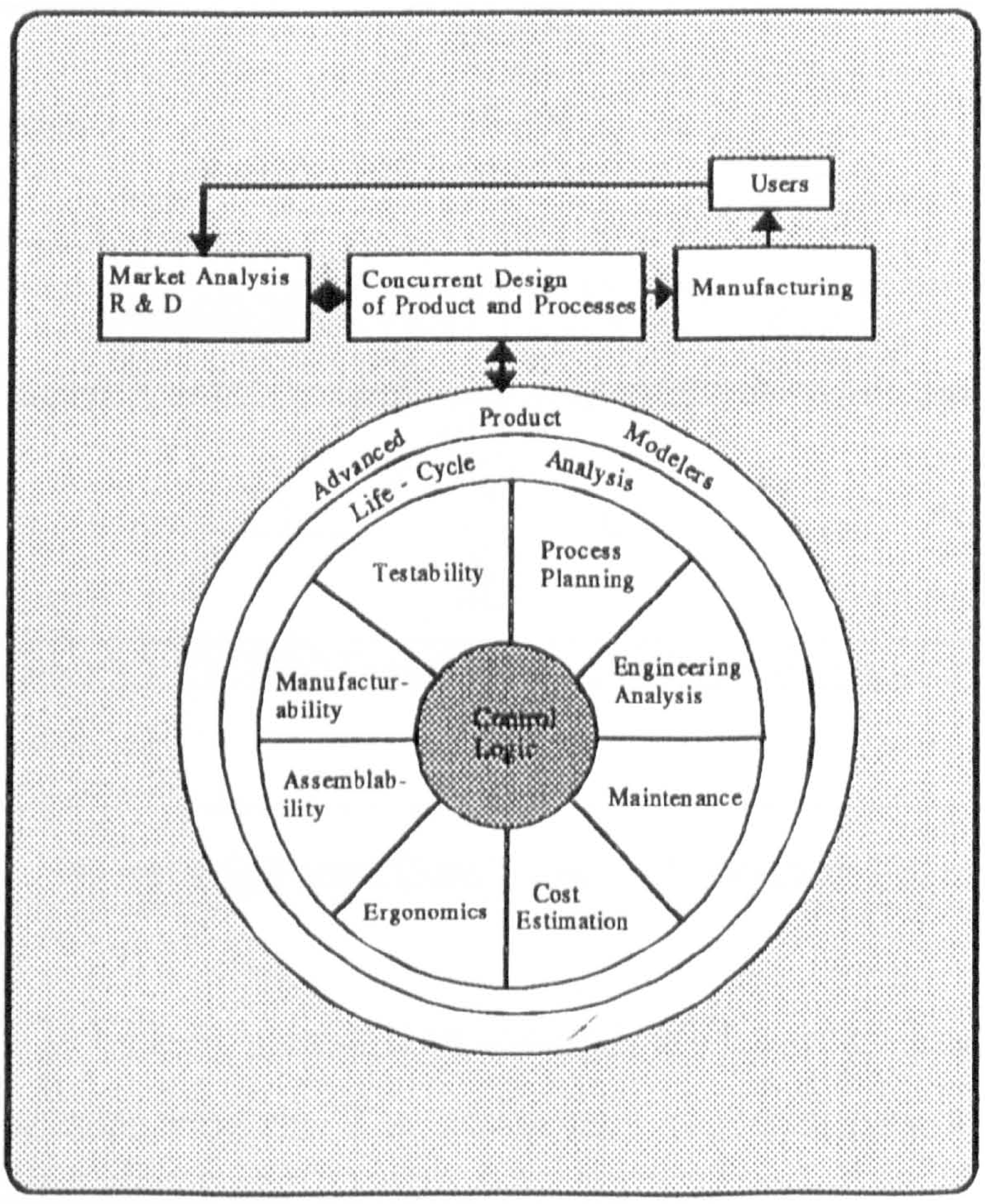


Figure (2.5) Product Development Cycle Employing "Concurrent Engineering Wheel" environment various down stream processes such as manufacture, and operation efficiency have to be considered as early as possible during the design stage. A model that represents the core tools for concurrent Engineering environment is shown in figure (2.6), Eversheim (1990).

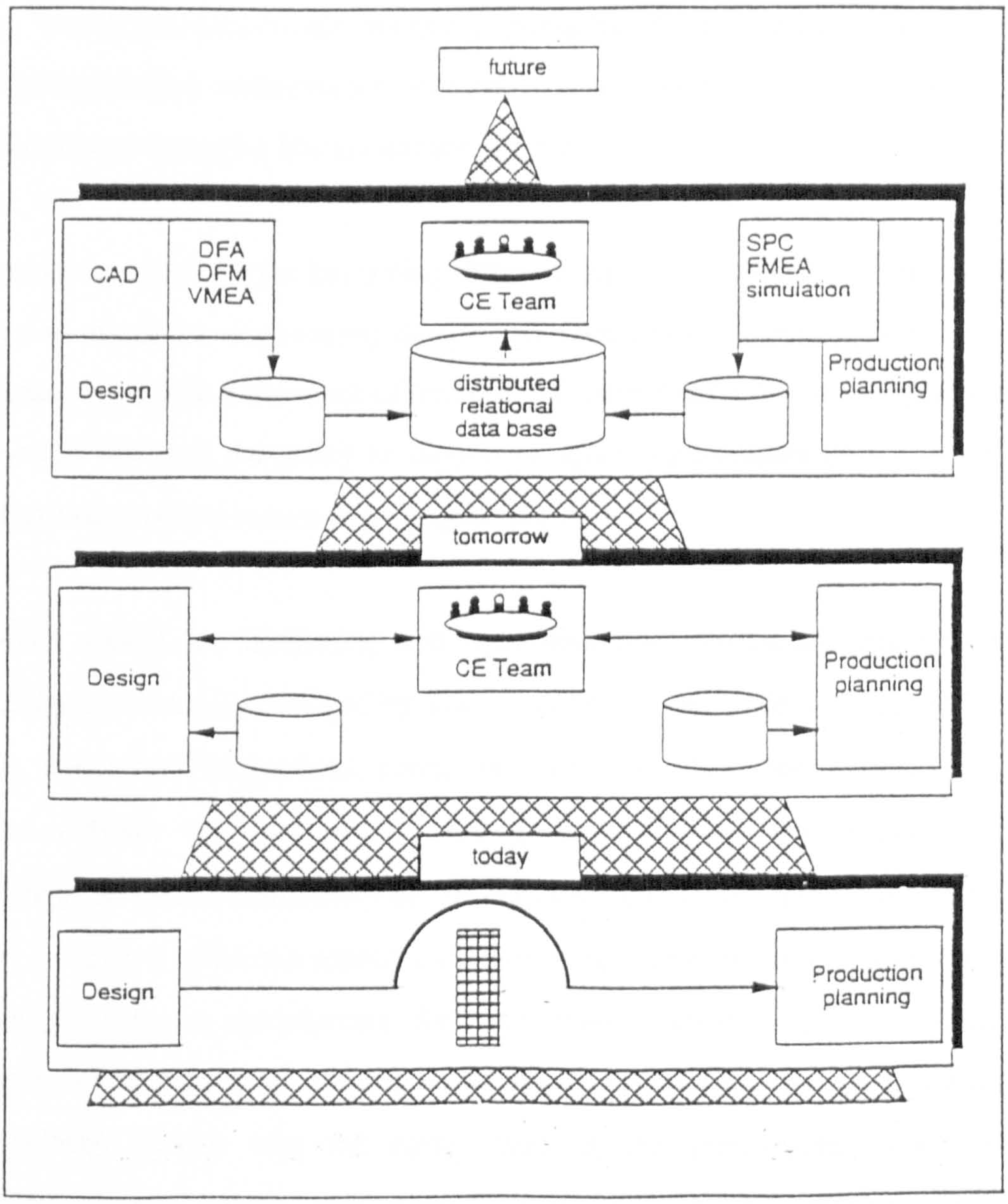


Figure (2.6) Future Core Tools for Concurrent Engineering

O'Grady, et al (1991) have presented an approach to Concurrent Engineering using artificial intelligence constraint networks. The system uses constraint networks that can advise the designer on improvements that can be made to the design. The advantage of this system that it is flexible enough to allow the design problem to be approached from a variety of view points. Dowlatshahi (1992) has provided a system approach to the design of mechanical components where the constraints associated with the design attributes of a concurrent engineering environment were presented. The proposed approach is capable of reflecting the results in an optimisation model leading to the identification of product configuration. Finger and Fox (1992) are developing a system that surrounds the designer with experts and advisors that provide continuous feedback based on incremental analysis of the design as it evolves. The system uses constraints as a language by which perspectives (e.g., comments on its manufacturability) communicate with one another and with the user. These perspectives are co-ordinated through a blackboard architecture.

An open system platform for integrating different engineering tools and management services in order to maximise engineering design and production planning efficiency is currently investigated within the framework of the ESPRIT project (CONSENS), Engelborghs (1994). The system will have the ability to support designers by monitoring the manufacturability and estimating production cost of a designed part.

A product model for facilitating and controlling the datasharing amongst multi-agent engineering processes is developed by Kott et al (1990). The model is comprised of hierarchy of parts, constraints, interactions, tasks, and employees. This model could be used by the Function Advisor (a prototype knowledge-based system that supports Concurrent Engineering) to assure consistency of the engineering decisions by propagating constraints through a network of human agents, and conveying engineering information to its users by identifying a relevant environment for their tasks. Glover et al (1991) described the significance of implementing the software tools "SYNTHESIS" to integrate Reliability and Maintainability (R&D) into the early stage of the product-life cycle development. SYNTHESIS tools enable each participant to productively contribute to concurrent engineering and the design decision process. This system can be seen as an effective tool for supporting Multi-disciplinary design teams which is a critical element of Concurrent Engineering. A Concurrent Engineering environment for micro-CAD systems, based on a commercially available local area network operating system, in order to provide adequate facilities for managing team-based design projects has been developed by Gay et al (1993).

Oh and Park (1993) have proposed an integrated decision model in which decisions on product and process design are simultaneously performed through economic evaluation at each stage. This approach minimises the product cost under a set of strategic constraints defined by the organisation. The model has been tested on designing a printed circuit board to demonstrate the effectiveness of a concurrent product and process.

2.3 DESIGN FOR MANUFACTURABILITY

Design for manufacturability (DFM) addresses the manufacturing-related concerns of individual piece parts. Boothroyd (1989) described the importance of the need to consider machining concerns while developing the design of a part, and illustrated several guidelines developed from a machining standpoint. Further research work is needed to enhance a computer-based framework that could enable designers to ensure that these guidelines are met.

Chung, et al. (1988) discussed a prototype system which links an expert system shell with a solid modeller and allows the user to construct the geometry using a set of design features. Higher level abstraction of the geometry and connectivity is maintained in the expert system for manufacturability analysis. Geometry representation based on features also allows easy integration with finite element methods for stress and heat transfer analysis. The results of the analysis can be further utilised in the expert system to determine potential defects that may occur during and/or after manufacturing. The expert system then recommends how to improve the design and eliminate potential defects. Hummel and Brown (1990) have investigated the role of features in the implementation of simultaneous product and process design.

Hayes et al (1989) proposed a slightly different method for using process planning knowledge to make design suggestions concurrently. This method is derived from observations of design suggestions made by human process planners as they made plans from manufacturing a variety of prismatic metal parts on a three axis vertical machining centre. The method is a process of iterative re-design which offers a way of using process plan information to find ways of reducing the cost of the design. It differs from other such systems in the way it produces the suggestions: most use recognition of patterns or features in the design but this method uses the structure of the process plan together with a catalogue of manufacturing alternatives to generate suggestions.

Stoll (1988) Ovens and Dekker (1987) Swift (1989) and Black (1989) proposed an approach for design for manufacture. The objectives of their approach were to identify product concepts that are inherently easy to manufacture, to focus on component design for ease of manufacture and assembly, and to integrate manufacturing process design and product design to ensure the best matching of needs and requirements.

Rhodes and Smith (1989) have developed a structured approach for the thorough processing of market information in order to establish a definitive product design specification, which is so essential to product success in the market. The approach comprises a number of steps with the emphasis on obtaining the full spectrum of information, the establishment of a comprehensive information base and its subsequent synthesis and analysis.

El-Gizawy et al (1989) have presented a strategy for concurrent product and process design or design for manufacturability. They described an approach for integration of product, process and tooling design and systematic method for acquiring and analysing information about capabilities and limitations of the manufacturing processes. The suggested strategy allows for timely evaluation of the effects of changing product and process design parameters on the performance of manufacturing as measured by cost effectiveness and productivity indices. Similar approach for quality control planning of mechanical components was proposed by Abdalla et al (1994j).

Thompson and Lu (1989) developed a methodology for representing and using design rationale. Design rationale is a remembrance of the design processes used during the execution of design activities. In their research, design rationale is represented in the form of design plans and design constraints. Their technique, recorded design rationale, can be used to help maintain consistent design description, provide explanations for designs, assist in making design revisions, monitor underlying design assumptions, and detect conflicts in current product and process design.

2.3.1 Taguichi Approach

A different approach to the design for manufacturability concept is described by Sutherland et al (1988). A frame work is presented based on Taguichi's model for the design process. The design process is described as taking place for: System design, parameter design, and tolerance design. In the system design stage, current experience and technological capabilities are applied to arrive at the most promising design alternative. In the parameter design stage, a parametric study and analysis of important factors of the design alternative is conducted to determine their optimal values. At the tolerance design stage, the loss function concept from quality control literature is used to select allowable tolerances for the important design parameters. The work by De Vor et al (1989) concentrates on the parameter design stage and implements the CE concept by identifying design, as well as manufacturing related parameters that should be considered at this stage. Design of experiments technique is used to specify the nominal values for the important design and manufacturing related parameters. The main selection criteria used is to identify those nominal values which minimise the transmission of functional variation to the output performance as a result of the presence of notice factors operating in the environment in which the product and process is functioning. The methodology has been demonstrated using the face milling process as an example. Feedrate, depth of cut, number of inserts, and cutter offset were identified as important process parameters. Mechanistic models, Sutherland et al (1988), were used to perform computer based simulations of the manufacturing process to determine the process parameter values.

2.4 DESIGN FOR ASSEMBLY

Design for assembly is a major sub-area in which significant work has been undertaken recently. Guidelines have been developed to enable designers to develop better sub-assembly and assembly designs so that "good assembly practices are designed into a product rather than planned into a production line,". Various schemes enabling designers to reduce the number of parts in an assembly and making it easier to assemble, the remaining parts have been proposed by Boothroyd (1989) and Aronson (1987).

Libardi and Dixon (1988) have reviewed research on the most relevant literature dealing with development of computer environments for the conceptual design of mechanical systems and assemblies. Selected literature is reviewed and discussed in relation to meeting the following requirements for such an environment: (i) representing and supporting top-down design, (ii)representing and supporting multiple functional viewpoints, (iii) representing functional knowledge, (iv) representing spatial relationships and geometry, and (v) maintaining consistency. Their study revealed that to meet the above requirements, a computer system should have the following features and capabilities:

- The ability to create and maintain several different representations of in-progress designs, including at least representation of the part of hierarchy(ies), geometry of subassembly and components, spatial relationships among subassemblies and components within and between abstraction levels in the part of hierarchy and functional viewpoints.
- A method for maintaining consistency among these representations.

Miles (1989) provided a technique that considers design for assembly and its role within a design for manufacture (DFM) programme, placing particular emphasis on those elements with which it has strong synergy, namely simultaneous engineering, product teams and other DFM technique. His technique focuses on a product's assembly at the design stage, as presented in figure (2.7). The assembly characteristics of a product should be established at an early concept phase of the design process when the opportunity for change is greatest. He also provided a few 'principles' covering good product design for assembly. Those principles are:

- Minimise variation.
- Ensure that each component is fully and correctly specified.
- Use symmetrical components wherever possible.
- Use a precedence diagram to check the sequence of assembly.
- If a part has to be asymmetric, then this asymmetry should be exaggerated.
- Minimise the number of separate parts that are used in the product.

- The product and components should be designed for uni-directional assembly.
- The number of assembly functions performed by each component should be minimised so that the number of individual parts within the product is minimised.
- Design the product to suit machine work ethics and principles rather than designing to human methodologies.
- Ensure that the orientation of a subassembly remains known and preferably constant throughout the assembly sound.

Ishii et al (1988) described the use of Design Compatibility Analysis (DCA) as a means of developing Computer-Based Tools to support design for manufacturability and assemblability. DCA focuses on quantifying the degree of compatibility between the design requirements (specifications) and a proposed design. It is a general means of suggesting improvements in the proposed design to increase the degree of compatibility. They suggest that this concept be extended to accommodate other life-cycle concerns of a product. The use of Knowledge Based Systems is proposed to capture compatibility knowledge associated with different product life-cycle concerns. This methodology has been tested in two domains: system design of power generation plants and design of mechanical products for assemblability.

Kim and Bekey (1990) proposed a framework for a knowledge-base software called an Assembly Expert (AEX) that will assist the designer to optimise his/her product design with respect to low cost and easy assembly. "AEX is intended rather as a subsystem of a general CAD system, but not as a substitute for a CAD". Li and Hwang (1992) have developed a framework for automatic DFA evaluation system development. The framework consists of five modules: assembly sequence generation; assembly features extraction; assembly code and other necessary operations generation; data manipulation and computation; and re-design suggestion. Their future work is directed towards linking a DFA evaluation procedure with a feature based CAD system. This is seen as a key step in achieving a concurrent engineering environment.

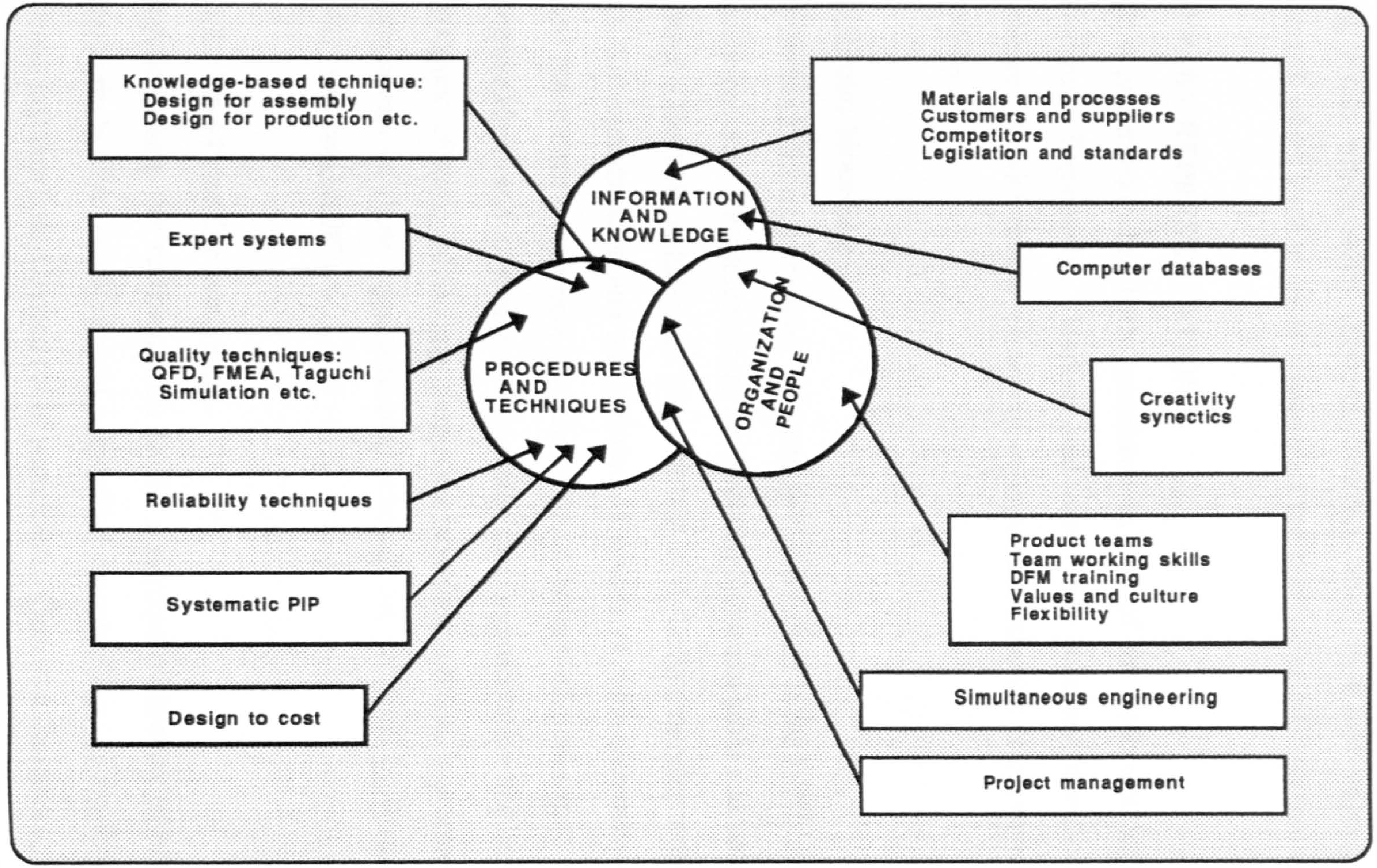


Figure (2.7) Key Elements of a Design for Manufacture Programme

Hsu et al (1993) have developed an integrated design-planning system that can be implemented to achieve assembly-oriented design through the feedback evaluation of a given assembly plan. The system aims at simplifying the redesign problem by focusing on the major areas of parallelism, assemblability and redundancy. These criteria provide re-design suggestions which, when properly executed, result in a new redesign that is assembly oriented, which leads to fewer components and operations, and less time to assemble.

2.5 PART REPRESENTATION

Part representation has been considered as one of the important topics in the area of Concurrent Engineering. Various part description schemes have been reported in the literature. A brief review of the most important schemes is presented in the following sections.

2.5.1 Solid Modelling

The solid modelling techniques and systems that emerged in the 1970's offer some important advantages over alternative means of describing industrial parts and products and are now gaining a foothold in industrial use of CAD/CAM. Solid modelling systems are concerned with the representation and manipulation of subsets of three-dimensional Euclidean space. They have three component representation, a means of performing operations on that representation, and a means of querying that representation for information. A brief description of some of the important solid modelling schemes is presented in this section. More details of these representational schemes are provided by Requicha and Voelcker (1982) and Jared (1987).

2.5.1.1 Pure Primitive Instancing

Modellers using this technique can handle a number of families of objects, each defined parametrically. A particular solid is specified completely by giving the family to which it belongs together with a limited set of parameters. Clearly, a disadvantage of such systems is that the range of objects that can be handled is restricted to those in the families pre-defined in the system.

2.5.1.2 Boundary-Representation (B-Rep)

B-Rep scheme is been used to represent objects by their enclosing surfaces or boundaries. A three-dimensional boundary model has data elements that correspond to faces, edges, and vertices. Boundary models are also called "evaluated models" because they store information in a form which is easy to compute.

2.5.1.3 Constructive Solid Geometry (CSG)

Using this technique an object can be represented in terms of a combination of so-called primitive volumes such as, cuboids, cylinders, cones, torus, spheres, and wedge, which can be added or subtracted by means of regularised Boolean set operators. These models are complete and valid representations of solids, they have syntactically guaranteed well-formed conditions and are compact over a wide range of solids. Extracting information from these models, however, requires a complex form of evaluation called boundary evaluation which converts the CSG structure to a boundary model.

2.5.1.4 Cellular Decomposition

This scheme represents an object by a list of the cells it occupies, cells are not necessarily identical. This method is very useful for modelling highly irregular solids, although the memory space requirement is rather high. This scheme has been used primarily in the areas of computer vision and medical imagining.

2.5.1.5 The Sweeping Modelling Scheme

This scheme is based on the fact that some solid shapes can be created by moving a line or plane on a defined trajectory. Designers often prefer this modelling scheme because the methods are easy to use. Cellular decomposition scheme has been widely used in the area of computer vision and medical imaging.

2.5.2 Feature Recognition

The database of contemporary CAD systems cannot be used to derive most CAM and CAE systems in an automated manner, since CAD systems do not produce enough information about the product. The information that is supported is in the form of low level details, from which higher-level information such as form features cannot be easily obtained. Several research efforts have been reported over the last few years in regard to feature recognition. Most existing approaches have to contend with difficulties, particularly with complex features which have an element of interacting faces. Typically these interactions may cause some or part of the feature to be entirely absent. Similarly, interactions between faces of distinct features may cause edges to disperse. Using a combination of Constructive Solid Geometry and Boundary-Representation may solve this problem. This section describes various techniques presented by previous authors to overcome these deficiencies. Lee and Fu (1987) proposed an approach, based on principal axis and tree reconstruction, to extract and unify feature representations. Their technique encompasses two steps for unifying manufacturing features: (i) tree reconstruction in which all participating nodes of the features are relocated and grouped together to form a subtree. (ii) tree transformation in which the subtree resulting from the above step is replaced by an equivalent subtree. This approach is based on constructive solid geometry (CSG) and does not require cumbersome computation of boundaries. However, it should be noted that a much wider study of a large variety of features is required to be conducted to define each individual feature and to co-ordinate the extraction and unification of multiple of features.

Wang and Chang (1990) have enhanced a technique for feature recognition using attributed adjacency graph approach, which was originally established by Joshi and Chang (1988). This method extracts basic cavity features from a design model and decomposes compound features as well as protrusion features into basic ones. The work is notable in that the manufacturing features were classified into two categories: Standardised Features and General Machined Volume/Features. To extract embedded manufacturable features from a finished workpiece design, one can reverse the machining process by growing a proper machined volume back to each machined face. An experimental feature recogniser that uses a combination of artificial intelligence and computational geometry techniques was presented by Vandenbrande and Requicha (1990). This technique is based on a generate and test strategy. Production rules generate hints (a characteristic combination of part faces) for the existence of features and post them on a blackboard. A test is carried through geometric computations, and the process continues until it produces a complete decomposition of the volume to be machined, which represents the amount of material to be removed in each operation to create this particular feature.

Owusu and Chen (1990) have developed a series of algorithms to recognise turned features from its scanned data. The proposed system has the capability to read the scanned data, to extract the geometric shapes, and to determine the connectivity of the geometric entities. the system uses the entity relationships of the shapes and rules to recognise the form features existed on a turned part. The system is capable of recognising a set of form features present on turned parts with only external features. Recognition of features present on prismatic parts are not included in the system.

Abdalla (1993) developed an approach to provide topological and geometrical information about the features in high level abstraction of a component that relates to design function or manufacturing characteristics. Further details about the scenario and theories of this approach are discussed in Chapter (4). Despite this technique has contributed effectively in interfacing CAD and CAPP, a number of problems particularly with compound features still ahead to be solved.

2.6 FEATURE-BASED MODELLING

The application of the Knowledge-Based Systems concept to design and manufacturing tasks has led to the recent development of distinctly different part representation schemes. Feature based part representation is one of these schemes. Features are higher order abstract geometric forms or entities, that are used in reasoning about the topology and geometry of designed artifacts during various design and manufacturing activities (e.g. fit, function, manufacturability evaluation, analysis interfacing, tool and design, inspectability, and serviceability), Cunningham and Dixon (1988). In such a part representation scheme, typical part features such as holes, bosses, slots, bores, cut-outs, threads, chambers, fillets, and grooves are explicitly defined unlike their implicit representation in most solid modelling schemes. Feature-based part representation schemes have been proposed fairly recently and work still under progress to establish their efficacy in design and manufacturing domains.

Choi, et. al. (1984) described an algorithmic procedure to identify machined surfaces (ie. machining requirements) for a workpiece directly from its 3D geometric description. A machined surface is a portion of workpiece that can be generated by a certain mode of metal removal operation. In their procedure, a machined surface is algorithmically recognised from a 3D boundary file, and then 2.5 D descriptions are obtained in a data structure (format) suitable for an automated process planning system. The simplified boundary file data structure is introduced in order to explain the machined surface recognition procedures. They defined a machined surface type as a pattern of faces and used a syntactic pattern recognition to find the machined surface from the boundary file.

Dixon et al (1987) have described how design can be done in three domains (extrusion, injection moulding, and casting) using the approach of Design with Features, and have shown how the resulting design geometry may be represented in data structure. The main advantage of this approach is in making it relatively easy to create higher level data bases, that can greatly aid the development of integrated design analysis manufacturing that share a single data base of information about the design.

Xue and Dong (1993) demonstrated a design feature-based model that supports feasible design generation, design details, and design performance evaluation by design feature-based knowledge reasoning using an intelligent CAD system. The manufacturing feature-based model facilitates evaluations on the manufacturability and production cost by representing a design using production process-oriented manufacturing features and production cost models. The author has not stated clearly the capability of this system to handle complex features or products.

Cugini et al (1992) proposed a slightly different feature recognition system. In their system the features are recognised in a technical drawing or in a 3D CAD model describing the part to be managed. The output of the recognition processes represents the recognised features as volumes in a hybrid geometric model. The system is designed by using conditional attributed systems, that allow the representation of both boundary models and technical drawings describing the solid as string of attributed symbols. These strings are rewritten by the use of rules describing features according to a given working context.

Shah and Rogers (1988), and Ludy et al (1986) described the functional requirements of different systems that will be capable of facilitating the extraction of higher-level information such as features. Shah and Rogers (1988) presented the design of a system that can be used both for product definition in association with solid modelling, and for driving engineering applications in an automated manner.

Features for tolerancing a solid model have been discussed by Ranyak and Fridshal (1988). They discussed the identified feature and tolerance classes, and how they may be used as the first level of a hierarchical feature model. The feature classes for tolerancing focus on the primitive elements of the part. The rule used for defining these classes is that each toleranceable feature must have only inherent tolerance value in each of the tolerancing categories. These primitive features are components of the more commonly used complex feature classes, such as slots or blind holes.

2.7 COMPUTER AIDED DESIGN (CAD)

This section presents a review of research in developing computer aided design systems to assist or automate the product design process. The main objective of this survey is to broadly characterise the research in CAD to determine if any relevant aspects of the simultaneous engineering concept have been addressed.

Alder and Ishii (1989) have presented a framework for evaluating designs and providing suggestions called design compatibility analysis, which incorporates both qualitative data (i.e. cost estimates) to produce an overall rating for a design based on functional specifications and target costs. They have used an object oriented language as a medium for describing designs and for sharing knowledge among several experts. Each expert can utilise various types of knowledge to reason intelligently about his/her domain (Heuristics, procedures and visual examples), and each expert can derive the questioning/reasoning procedure through action rules, which can be triggered upon creation/deletion of an object or creation/modification/deletion of an attribute. Throughout the research, they have used examples from three domains to illustrate various concepts: functional design of mechanical systems, design for assembly, and design for injection moulding.

Howe et al (1986) have presented a model of design where the task is viewed as consisting of several cycles of evaluation and redesign. The inputs of that system is a set of problem parameters describing physical constraints on the design, a set of performance goals, and an initial design procedure. The system evaluates the initial design and identifies its weaknesses. The program then selects design variables, proposes changes in the variables, assesses the overall effect of the changes, and implements it if the effects are positive. The evaluation and redesign cycle continues until the design is judged acceptable.

Tong (1987) has presented a framework for organising, evaluating, and developing knowledge based models of the design process. He assumed that evaluation of design process model can be carried out from three usefully distinguished perspectives: the knowledge it embodies; the functionality of the design process, from a problem-solving viewpoint; and the implementation of the design process as an actual program. He focused in this research on the first two perspectives and introduced a set of basic functional components, and showed how existing approaches, or systems, can be viewed as configurations of these components, in which domain knowledge has been incorporated.

Bengu (1993) has introduced a design optimisation system which integrates analytic and simulation techniques for optimal design of continuous review inventory systems using a knowledge-based framework. The knowledge-based framework was used to interface with the user to capture a problem knowledge, choose and execute the suitable technique, validate the approach and finally prescribe a solution. The primary goal of the system was to consolidate the analytic and simulation techniques relevant to a problem domain.

A dynamic decomposition strategy in the conceptual modelling of design objects was discussed by Rosenman (1993). His approach addressed more important issues, such as multiple and dynamic views, of decomposition for a compete and efficient conceptual modelling schema. Other Schemes are considering only the issues of generalisation, specialisation and aggregation decomposition relationships. It can be concluded that the proposed approach helps in generating an environment which considers various discipline's views involved in the design of an object.

LeBlanc and Fadel (1993) have investigated the design decomposition from a data modelling and an object-oriented paradigm (OOP) perspectives. Their research has focused on considering alternative "views" that a design should posses. Coad and Yourdon (1991) have selected a data modelling technique, called object oriented analysis to build a data relationship model of the engineering analysis phase of a design and results in an object-oriented product model (OOPM). The major advantage of this system is the analogy between different classifications in the design process and in objects-oriented environments.

2.8 FEATURE BASED DESIGN BY CONSTRAINTS

Design by constraint leads to producing a product with concise specifications, shorter lead time, and less cost. It allows designers to design their products within the available manufacturing facilities, and meeting the desired product specifications. Design by constraints approach reduces the amount of information storage and data-flow requirements. Mark, et al (1991) proposed a feature-based generative design by constraints, the system requires the user to specify solutions in terms of manufacturing data, which is captured by means of an interactive simulation of machining processes, in which the constraints of materials, tools and equipment are displayed to the user.

Silverstein and Sun (1990) described a constraint management system called "CONSYST" that was implemented to create a knowledge-based application for circuit layout design. In this system, several key domains consisting of design, tools, cost analysis were considered as key domains of the product life-cycle. CONSYST supports various number of functions, such as providing a constraint representation template for creating and editing constraints; evaluating constraints automatically; providing a classification scheme for constraints; and providing advice whenever a constraint is violated. The weakness of this system at its current stage is that it deals with a very narrow domain. But it can be seen as a successful step towards developing a constraint KBS for supporting CE strategy.

A paradigm for constraint processing in the design process was proposed by Godden (1991). The technique is based on a backtracking search algorithm and a unification algorithm that is sensitive to the status of logical formulae. It facilitates the construction of automated post-design analysis tools that support constraint based design evaluation that does not necessarily require the satisfaction of all constraints. The system operates by iteratively applying each constraint from a database of constraints to a part design and determining the status of each constraint. The drawback of this system is that it relies on the user to observe and rectify constraint conflicts, rather than suggesting alternative solutions.

A constraint knowledge based system for supporting a mechatronics design environment was discussed by Lee (1994). The system at this stage can only be used to assist designers in optimising the assembly process of a printed circuit wiring board. Further enhancement to the system is currently undertaken to improve its ability to optimise a component placement and track interconnections.

2.9 COMPUTER-AIDED PROCESS PLANNING (CAPP)

In the manufacturing environment, process planning can be defined as the act of preparing a detailed plan for the production of a part or assembly. The selection and sequencing of operations necessary to transform the raw material into a finished part is its primary objective. Process planning is an activity which is very important to orderly and efficient operation of the manufacturing enterprise. Once the product has been designed, work of the process planner probably has more impact on the cost, quality, and rates of production than any other activity of the enterprise.

Creation of a process plan in which process capabilities are mismatched with product requirements can result in excessive scrap and re-work, low output, an excessive process inventory and high production costs. Alternatively, well formulated process plans can provide products of the required quantity in the desired quality on the planned schedule and at a minimal cost. Currently, the process planning activity is carried out with a number of Computer-Based Decision Aids that assist or automate the process planning task. This section presents a classification of such CAPP systems with the intention of studying if these systems address issues pertaining to the design concept.

Mill et al (1993) have discussed the major difficulty encountered in the development of advanced and integrated CAD and CAPP systems. Their discussion has shown that neither simple feature oriented design nor feature recognition methods alone can fulfil the requirements of advanced systems. Satisfactory modelling of the interactions between features in a component is a prerequisite to establish such a system. Crawford (1993) has proposed an integrated feature-based B-Rep solid modeller and process planning system by using features in a common product model database. A description of the feature hierarchy and organisation was given, together with the commands available in the process planning toolkit to navigate and interrogate the feature model.

Abdalla and Ikonopisov (1993) proposed a feature-based design for process planning. The model is based on CE strategy. It evaluates all decisions connected with component design and matches them with the knowledge-base rules. It proposes possible changes of the inapplicable design features. It uses part features, manufacturing knowledge, machine tool data, cutting tool data, material data, and goals as initial information for generating the required process plan. The system utilises manufacturing knowledge (rules and equations) for estimating the process cost and manufacturability of the component.

Allen and Smith (1980) presented a different process planning system which is called Generative process planning. The system is designed to automatically synthesise information to develop the process plan for a part. They also combine a manufacturing logic module with a suitable part description scheme to generate the process plan for a particular part. The use of decision tables and trees to capture manufacturing logic is explored, and has been applied to generative process planning.

Gindy et al. (1993) described a hierarchical structure for form features definition and classification, and an information structure which can be used for developing process plans for prismatic machined components. They also outlined some of the methods for representing the form-generating capabilities of machine tools. In addition to elaborating how the models are being used for reasoning about component geometry during plan generation and process optimisation strategy at the feature and component levels for the determination of component set-ups.

Liau and Young (1993) have developed a Process Planning and Concurrent Engineering system called PACE, that implements Printed Circuit Board (PCB) process planning knowledge formulated as constraints to build interactive process plans and to assess their manufacturability. PACE has the capability to generate process plans for PCB assembly from design attributes and to keep consistency between PCB design and the existing production facility. Further study is needed to enhance PACE to generate process plans for applications other than PCB, as well as taking into consideration other functions during the design stage.

Hummel and Brookes (1986) and Held et al (1992) have developed an expert system, which can be used to generate process plans for the production of machined piece-parts given a feature-based part description. The input to this system represents each part as a collection of manufacturing features, where each feature is a region of a part which has some degree of manufacturing significance. Each feature is characterised as a structural entity whose attributes specify lower-level topology, geometry, or tolerance information. They have introduced in their system a structure for representing features using symbolic and object-oriented programming techniques.

2.10 KNOWLEDGE-BASED SYSTEMS IN A CAD ENVIRONMENT

The integration of the knowledge-based systems with conventional software eg., CAD systems, calculation and simulation modules has introduced significant benefits in the area of Concurrent Engineering, Design for Manufacturability and Design to Cost. The integrated systems enable designers to improve the manufacturing process, reduce production cost and significantly improve the quality of the product. Moreover, a continuous flow of information between design and manufacturing processes reduces the number of cycles needed to achieve a working prototype.

Abdalla (1994g) have developed a *Concurrent Engineering Design Environment* (CEDE) which consists of an integrated KB and CAD system. The system addresses the issue of lowest cost design strategy of a part by concurrently taking into consideration different product life-cycle concerns during the product development stage. It also facilitates simultaneous consideration of various activities such as analysis and refinement of product and process data. The System gives a predictable machining cost estimation and continuous feedback to designers concerning possible manufacturing issues or requirements as the design proceeds. This approach is a fruitful way of showing the design feasibility as well as reducing the timescale and cost of the product design.

Held et al (1992) proposed a knowledge-based enhancement of conventional CAD that meets the requirements of complex mechanical design tasks. Their enhancement is based on the explicit representation of design knowledge. Special attention was directed towards representing, evaluating, and inferring dependencies restricting design alternatives. Above all, the integration of the knowledge-based systems with conventional software CAD is being carried out.

Vaghul et al (1985) have demonstrated the "designing with features" approach for developing expert systems that interactively evaluate manufacturability of designs being created on CAD systems. This approach uses feature-primitives in a front-end to standard CAD systems which directly creates a data base of information about features.

Willis et al (1989) and Uemura et al (1988) outlined the development of a process planning system using knowledge-based techniques with derivation of component geometric information from a three-dimensional solid modeller. The knowledge-based components of the system are centred on a production rules based expert system, coexisting with a non-linear knowledge-based planning system. These are in turn coupled to a solid modeller via a geometric interface. The knowledge resident within system operates on the geometry of the component to produce the planning and control data.

The development of a Computer-Based Integrated Engineering Design Environment which facilitates design decision-making by providing a medium for increasing communication and co-operation amongst product development participants has been carried out by Lu and Thompson (1988). Within this system, product and process designers can integrate the recommendations and expertise of all product development concerns as early as possible within the design-cycle.

A model for integrating multiple sources of knowledge within an engineering expert system is presented by Mayer and Lu (1988). The system allows possible conflicts between multiple knowledge sources to be logically resolved at run-time rather than during the knowledge acquisition stage. Unlike the traditional approach in which the knowledge engineer is responsible for resolving conflicting views, resolutions are dynamically accomplished by the knowledge sources themselves and/or by system users. The system user is included as a problem-solving colleague to select a proper strategy from those offered by different experts. Both qualitative and quantitative constraints are traced during problem solving and can be retraced if necessary. Other similar approaches have been demonstrated by Its et al (1988), Rayson (1985) and Wang (1988).

2.11 KNOWLEDGE-BASED SYSTEM FOR COST ESTIMATING

Many companies making goods to customer order have problems in estimating their manufacturing costs. These problems increase as the product becomes increasingly customised, and cannot be built from a range of standard products and sub-assemblies. Cawthorne-Nugent et al (1989) have described a Cost-estimating System which develops a Feature-based Description of the product and a description of likely problems with communicating and interpreting order-related information. These descriptions are used by the system to match the enquiry to similar orders that the company has completed in the past.

Dewhurst and Boothroyd (1988) have developed a procedure which is intended to form a basis for cost estimating in the early stages of product design before detailed design has taken place. When it can be assumed that efficient manufacturing will subsequently be carried out, tool costs can be incorporated into manufacturing cost estimates before detailed process plans become available.

The need to arrest and reduce costs at all phases of the life cycle of aerospace systems is becoming increasingly important due to many external factors. Qualitative and quantitative data on cost drivers are useful for designers consideration during the design, manufacturing, operation, and maintenance of aerospace systems. Opportunities to minimise costs at the conceptual and preliminary design phases are suggested by Noton (1983).

London et al (1987) developed an expert system for cost estimation and manufacturability feedback. The system provides mechanical engineers with first order manufacturing cost estimates and manufacturability feedback very early in the design process, concerns process limits and design inconsistencies during preliminary design.

A knowledge-based system (KBS) for cost effective design based on a solid modeller was developed by Abdalla (1994h). The KBS captures topological and geometrical information about the model features and estimates the machining cost for these feature at each stage during the product life-cycle development. It then recommends, how to improve the design and eliminate potential defects. This approach enables designers to minimise the machining cost and improve the product quality.

2.12 SUMMARY

Literature in major areas related to this research is reviewed in detail. In the area of concurrent engineering, it has to be mentioned that CE philosophy utilises a cross-functional team approach to get the pertinent players involved in each stage of the product development cycle. Some of the principal requirements for implementing concurrent engineering strategy have been discussed by Parasad, et al (1993).

Working relationships between people was identified as one of the main imperatives for implementing CE. Extensive training in team building, leadership, and the CE plan prior to actual start were some of the lessons learned from the implementation of CE at OECO Corporation, USA, Monroy (1992). Benefits reported were significant, an overall lead time reduction, reduction in engineering changes by 40%, reduced unit costs, and general improvement in the product quality and reliability. Burhanuddin and Randhawa (1992) have described a system that integrates product design specifications with material and process databases, and a simulation based analysis module. Their system allows product designs to be evaluated economically and technically, and to identify the best production environment.

In the area of Design for Manufacturability it was indicated that recent work has been concentrating on presenting a strategy for concurrent product and process design. In the area of part representation, it was pointed out to be a central concept in the area of design for Manufacturability/cost. Two different kinds of part schemes are reviewed: Solid Modelling and Feature-Based Schemes. Some researches have given a considerable attention for developing Computer Aided Design to assist or automate the product design process. In the area of Computer Process Planning, different systems such as Semi-Generative and Generative Systems were reported. It is pointed out that the models of the design process and the process planning systems need to be extended to address manufacturability. In the areas of Knowledge-Based Systems in a CAD environment and Cost estimating, most of the work had concentrated on integrating the KBS with the CAD environment.

It can be noticed that little attention has been paid in previous research work towards developing a system which provides a generic support and cost estimates to designers at an early stage of the product life-cycle development. In this research a concurrent engineering design environment has been developed for facilitating parallel execution of some of the engineering activities.

CHAPTER 3

THE CONCURRENT ENGINEERING DESIGN ENVIRONMENT

3.1 Overview

This chapter illustrates a general framework for an architecture and a methodology developed in this research work to support concurrent product and process design. The principal elements for establishing an intelligent design environment are also discussed. In addition to further details on the classification of process related concerns. It was postulated from the literature survey, which is reported in Chapter (2), that many of the computer systems developed todate, especially in academic circles, have not given the solutions which are required. This research work has endeavoured to build a generic platform for an intelligent design environment for supporting a Concurrent Engineering Strategy.

3.2 Introduction

Concurrent Engineering (CE) refers to the practice of incorporating various values of a product into the design during the early stages of development. These values address the entire life-cycle of the product and include not only its primary functionality but also assemblability, producibility, serviceability, testability, and even recyclability. It utilises a cross-functional team approach to get the pertinent players involved in each stage of the product development cycle. Therefore, parallelisation of various activities, data standardisation, and integration of the product development process are critical criteria in implementing CE (Abdalla 1994i).

Some of the principal requirements for implementing concurrent engineering strategy have been discussed by Abdalla (1994a and 1994g). His study highlights the possibility of collaborating designers to proceed independently, correlate interdependency, use existing information (data, knowledge, and processes), in addition to negotiating conflicts arising from design inconsistencies. This work raised a series of research issues fundamental to the enhancement of concurrent engineering practice.

A number of definitions have been given by various authors to CE strategy. For example, Keys et al (1992) define CE as: "A systematic approach to the integrated simultaneous design of a product and the related processes, including manufacturing and the other support functions". Shina (1991) defined CE as: "The earliest possible integration of the overall company knowledge, resources, and experience in design, development, marketing, manufacturing, and sales into creating successful new products, with high quality and low cost, while meeting customer expectations". These definitions indicate that all parties concerned with the product life-cycle of the product should have significant influence on the design of the product. Therefore, the functional barriers between departments, which have created a strict sequential flow of activity, time wasting and inter-departmental communication, should be removed.

In essence sharing data across the different product-life cycle domains is a fundamental rule for practising CE, and appropriate IT tools have to be developed to facilitate this task. The application of IT can effectively provide support to a CE approach by integrating the disciplines such as CAD/CAM, CAPP, and KBS in which computer systems already have a well established role.

3.3 The Proposed Concurrent Engineering Design Environment

There are at least two different approaches for implementing the concept of Concurrent Engineering. The first approach is to design parts to be manufacturable in existing manufacturing facilities. The second approach is to concurrently develop the design of the part, design of the facility, and, the process plan for the facility. These two approaches define the two ends of a Concurrent Engineering Spectrum in terms of the degree of concurrence that is achieved. In the second approach, all three tasks namely product design, facility design and process planning are performed simultaneously and "maximum simultaneity" can be achieved. In the first approach, facility design is not performed and only product design and process planning are carried out concurrently. The concept of this approach has been developed and implemented in this research. This approach ensures that the designed part can be manufactured using the existing manufacturing facilities for the lowest product development cost. It is also designed in such a way to enable designers to resolve concerns which might arise due to design inconsistencies or constraints in the existing manufacturing facilities, by making the necessary changes as early as possible during the product development process.

3.3.1 System Characteristics

The benefits and characteristics of the proposed approach can be summarised as follows:

- it enables designers to automate tasks by applying a problem solving and decision making ability using a knowledge-based system;
- it facilitates a designer or a group of designers a capability to carry out concurrent design tasks and to get advice from the system regarding design inconsistency and;
- enable optimisation of the design processes based on historical data or expertise from the same or similar domains.

3.3.2 System Requirements

Achievement of the above features is a significant challenge in which five major problems have to be addressed before accomplishing system realisation. These major issues can be summarised as follows:

- Topological and geometrical recognition of features in high level language (abstraction).
- Integrating a Solid Modeller with both a Knowledge-based and a Process Planning System.
- Developing a Reasoning System which can provide feedback about manufacturability concerns such as process limits or design inconsistencies.
- Data Sharing Management.
- Decision Making Support.

3.4 The Structure of the Proposed System

The proposed design environment consists of six major modules, Product Design, Feature Recogniser, Engineering Database, Process Planning, A Constraint Knowledge-based System, and Cost Estimating module as shown in Figure (3.1). All these components interact one with another according to the type of the information needed and the user request. It allows the user to work in a flexible manner in terms of gaining access to any specific level of the design processes. An overview of each component of the proposed system is given

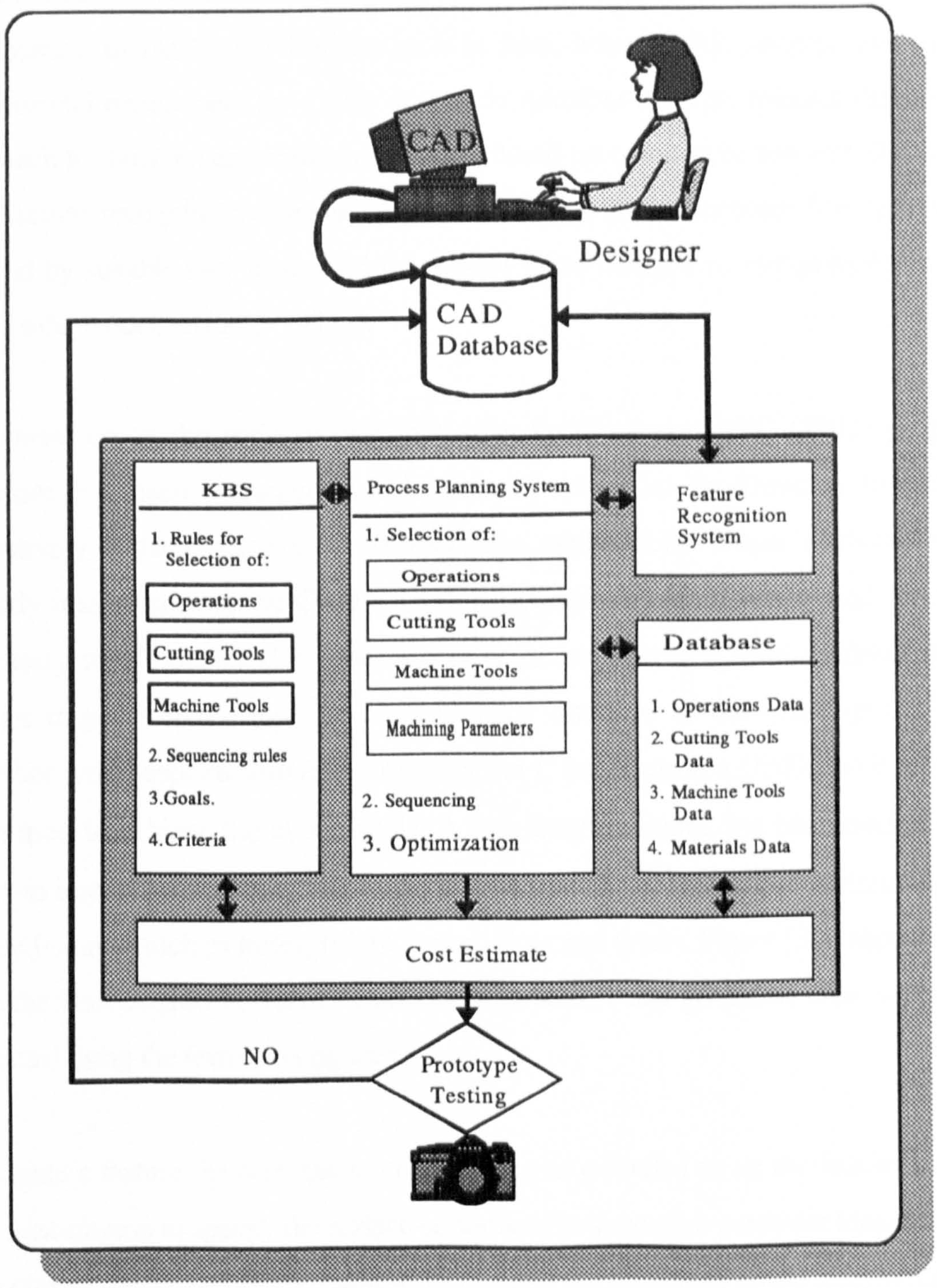


Fig (3.1) The Concurrent Engineering Design Environment very briefly in the following sections. Further details concerning the structure and work scenario as well as the implementation of each approach are discussed in the subsequent chapters.

3.4.1 Feature Creation and Recognition

Recognition of machinable features such as slots, holes, drafts, pockets, and rounds is a fundamental requirement for a fully automatic manufacture. This research demonstrates an approach for creating and extracting features based on commercial software (Pro/Engineer). The feature recogniser is capable of performing two main functions; first features can be defined by suitable user input; and the second is the function to recognise features from a given solid model, Abdalla (1994g).

An extension to the solid modelling system Pro/Engineer, PTC (1991) programming interface has been enhanced in this research using its Pro/Develop module to co-operatively assist designers in creating new applications. These applications can be directly integrated into the CAD System (Pro/Engineer) environment and to extract the necessary topological and geometrical information from the solid modeller during the design stage. Pro/Develop, the programmatic interface of the Pro/Engineer database, together with bespoke software written in the C language in a UNIX environment, have been used to achieve the above goals. A user interface menu has been created to enable users to interact with the system easily and efficiently. This interface includes facilities to create features such as holes, fillets, round, slots and drafts. Figure (3.2) shows samples of both the User-defined Features.Menu and the topologic and geometric data which could be extracted using the feature recogniser.

To create a feature the user has to choose from an extended menu the feature's name/icon. The next stage is to specify the surface or surfaces to attach this particular feature, the system then checks the legality of the request. In the case of constraints satisfaction or legal request the system starts automatically to match first the required feature specifications with the available features specified in the user-defined features domain as well as in the library. The new feature is then generated, positioned, and oriented, but the user at this stage still has the flexibility to modify, update, or even suppress the constructed feature when it is necessary. In

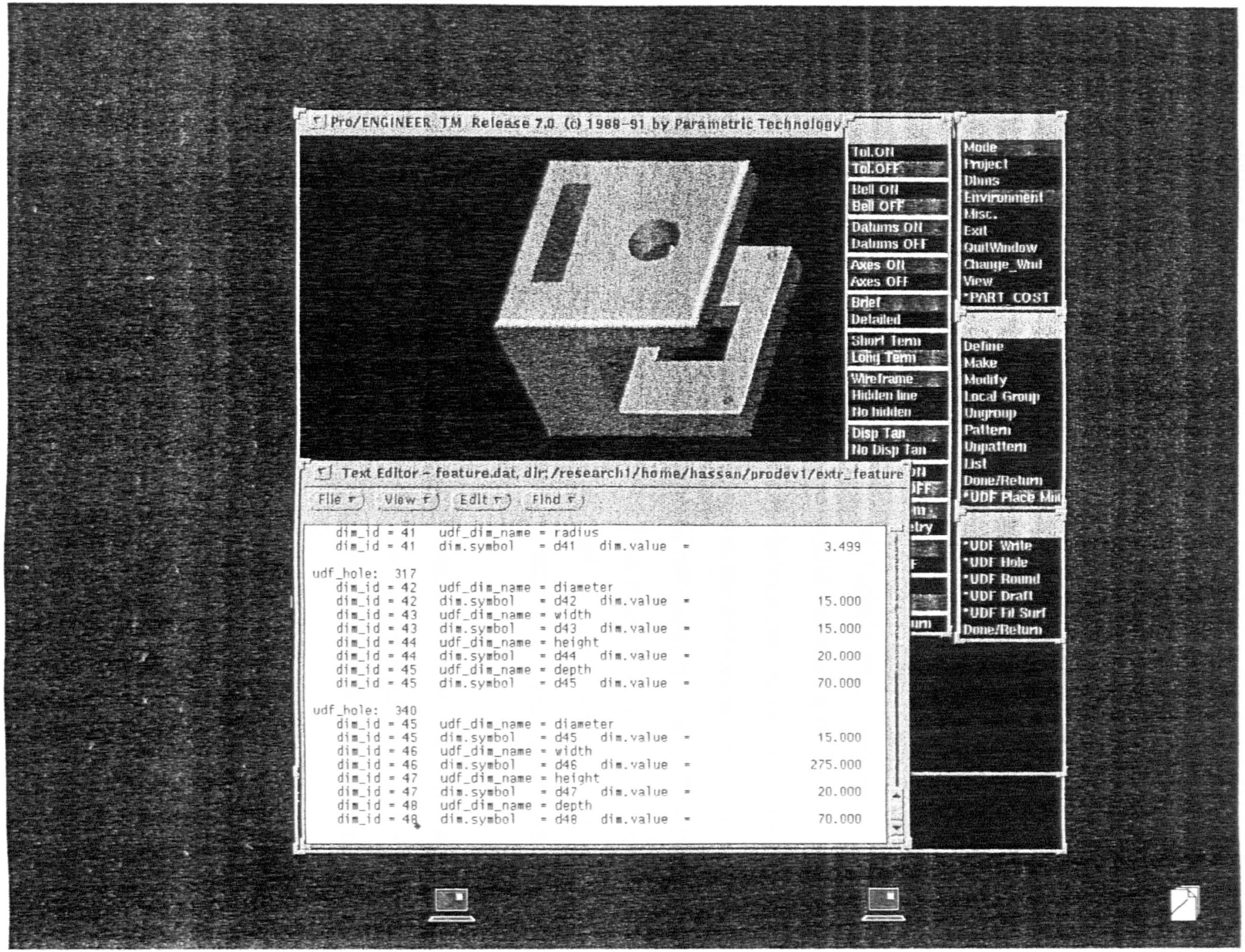


Figure (3.2) The Enhancement Interface to the Solid Modeller this manner the system performs the user's command without engaging the designer with potentially tedious steps as required by most current solid modelling systems.

This enhancement is being used for various applications which are based on geometric reasoning such as;

- Analysis and design optimisation.
- Getting access to meaningful data in high level language (abstraction).
- Facility for geometry modification by the user, etc.

3.4.2 The Knowledge-based system (KBS)

The advent of Artificial Intelligence systems has introduced a wide variety of knowledge representation schemes such as frames, rules, and logical terms. A Knowledge-based system toolkit, Knowledge Engineering Environment (KEE) developed by Intellicorp (1989) was chosen for both knowledge representation and decision making support in this research. The system was built on a SPARC Station (SUN4) as the development platform. KEE supports frame-based-objected-oriented programming and rule-based reasoning. These rules consist of a series of necessary and sufficient conditions. Each object in KEE is represented as a single frame called a unit, and each unit is composed of slots. Each slot contains data or a procedure which describes the characteristics and behavior of a particular object.

The KBS supports a number of tasks, such as selection of materials, selection of machines, selections of machining processes, and calculation of machining time and cost. It has also been used for structuring the expert knowledge for the product and facility features.

3.4.3 The Process Planning System

After creating the component with the solid modeling system, the Feature Recognition System (FRS) defines and extracts the information needed for machining the component's features (slots, holes, etc. and their attributes and sends them back to the Process Planning System (PPS). The PPS "ENGIN" shown in figure (3.3) is used to generate a process plan. The system has a KBS which includes decision table techniques, formula, rules, and dialogue mask which are used to generate a process plan. It has also a Repeat Plan module which includes planning of previous finished parts,

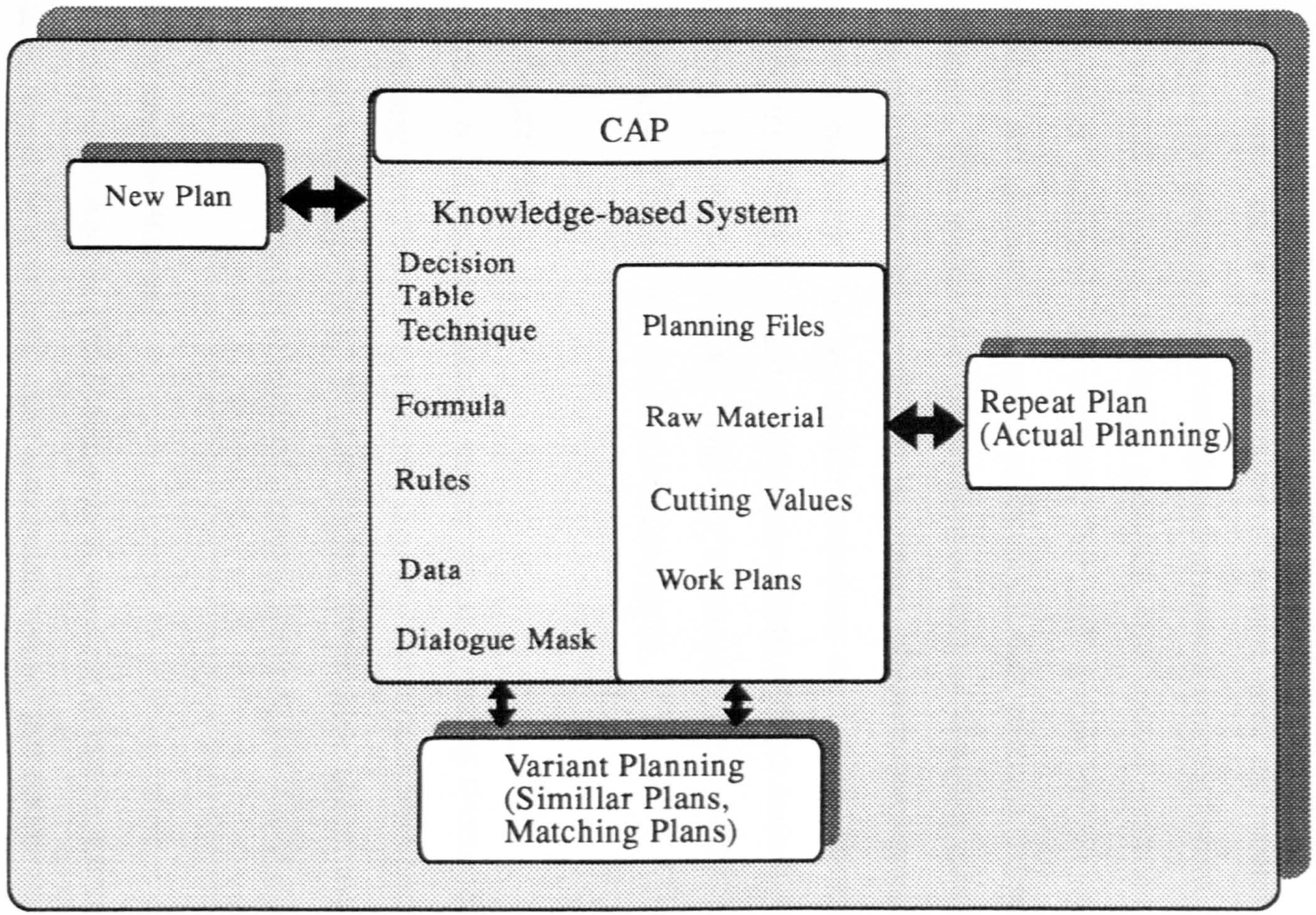


Figure (3.3) The Module of the Process Planning System this data has been used to generate a work plan of similar parts without unnecessary additional data input as is common with most of the currently available process planning systems.

Once the PPS receives the necessary information from the FRS, it starts to select the machining operations, machine tools, cutting tools and machining parameters. Priority rules, based mainly on a set of factors in terms of relative cost, tool accessibility and availability, determine the selection of the manufacturing method for each feature. Whenever a high priority method is found not to be applicable, the exceed constraint and the corresponding product parameters are recorded. For each feature the set up and the operation sequences are generated according to the orientation, relations and connections between the features. The system also considers the effect of changing either the part characteristics or the manufacturing facilities on the product life-cycle development, in terms of cost, time, and consistency. The system then sequences the selected operations and calculates the machining time, cost, and examines the results with the desired goals (such as minimum cost). Users can interact with the system in terms of modifying the generated process plan if it does not match the desired goals.

3.4.4 Database Engineering

The database contains information essential for the process planning system included are material and machining operations data, including accuracy and surface finish corresponding to a particular machining operation. It also implies information about machine tool capabilities, and technological output in terms of accuracy, feed rate and cutting speed.

3.4.5 Machining cost estimation

The system developed by Abdalla (1993) includes an interface to enable users to interact with the system regarding machining cost estimation during the design session. The interface has been carried out using the KEE function facilities and designed to enable users to obtain information about not only the total cost but also the individual cost elements such as turning, milling, drilling or reaming, tapping, centre drilling and set-up cost. If the cost of the product exceeds the targeted cost, then the system may suggest discontinuing further development or redesigning the product. The system is developed in such a way that it collects data from various engineering activities in a CE environment and evaluates the design based upon the predicted costs of machining, assembly, material, testing, overhead and other drivers. This cost estimating system differs from conventional product cost estimating systems, in that it is structured to support Concurrent Engineering.

3.5 A Working Scenario

The normal procedure for designing a product using this system is that the designer should begin with the enhanced CAD system to create a part and its features using the Feature-Recognition Interface. At this stage once the designer finishes creating part of, or all the form features, the Feature Recogniser System (FRS) immediately starts to extract geometrical and topological information needed for machining of the component's features. The system at this stage is capable of defining a set of features, such as slots, holes, rounds, drafts, and fillets, and their attributes. On the other hand, the KBS contains extensive rules, criteria, and goals. The rules in terms of operations selection, cutting tools, and machine tools. The targeted goals in terms of the preferable final characteristics of the final product, and this is directly linked with the company's strategy and customer expectations. For instance some products are cost based, others are quality based and the selection of the machining operation is a function of these goals.

A major advantage of such a system is that it will allow evaluation of all decisions connected with component design and match them with the knowledge-base rules. It will propose possible changes for inapplicable design features. It will use part features, manufacturing knowledge, machine tool data, cutting tool data, material data, and goals as initial information for generating the required process plan. Manufacturing knowledge (rules, equations, and formulae) is then utilised for estimating the process cost and manufacturability of the component. So the degree of concurrence enables users to avoid design inconsistency.

3.6 SUMMARY

The proposed approach facilitates the process of concurrent product and process design. It provides facilities for designers to share engineering data including geometrical information, shapes, volumes and spatial relations. It also has the facilities which enable designers to modify, update or define geometrical information about design. The object oriented programming and the rules of the reasoning system (KEE) will be implemented to establish a technique for managing or controlling the sharing of various types of data and to keep consistency.

CHAPTER 4

AUTOMATED RECOGNITION OF FORM FEATURES FROM A 3D SOLID MODELLER

4.1 Introduction

Current CAD systems represent drawings in two dimensions, wire frame models, surface models, solid boundary representation or solid constructive geometry models. This implies that the product is represented by sets of points, lines, surfaces and/or primitive volumes. This type of representation is not suitable for most manufacturing applications. It may be sufficient for tasks such as the computation of areas, volumes, or the presentation of geometry, but other applications such as Cost Estimation, Design for Manufacturability, Process Planning require a completely different type of information, Wierda (1991). The consequence of this is a lack of intelligence and limited capabilities in current CAD systems. An example of the lack of intelligence is that they do not support non-geometric information such as functions, Kikkawa et al (1993). The lack of intelligence of the current CAD system restricts designers from working on a top-down design technique because of the lack of design detail at different levels. Additionally they do not possess appropriate knowledge representation schemes to address down stream design and manufacturability concerns. The availability of such an intelligent CAD system would address the above deficiencies in order to enable designers to consider downstream and top stream activities simultaneously during the product life-cycle development stage. For instance, in most of the current process planning systems planners have to describe the topological and geometrical information of a feature manually. This technique has been seen as a tedious, inaccurate and an inconvenient methodology for today's advanced manufacturing systems.

A way to overcome many of the above problems is to implement an Automated-Feature Recognition approach to extract information from the CAD database directly. However, feature recognition has gained considerable attention in the research arena but many research issues associated with this aspect remain unresolved. Luby, et al (1986) described a possible method, called "designing with features", and have demonstrated a symbolic representation scheme of design geometry based on features. Their prototype does not have a rich enough set of features to enable the design of complex parts without an explosion in the number of primitives. Requicha and Vandenbrande (1988) proposed system architectures in which design is done by traditional solid modelling methods as well as through functional features, which are then translated into standard CSG (Constructive Solid Geometry) representations, and these representations are converted into features relevant to manufacturing or other applications by a feature recogniser. The deficiency of their approach is that it does not deal with either feature interactions or complex features.

A description model for feature-based modelling was proposed by Falcidieno et al (1992). The system consists of a primary representation in terms of shape features and a set of viewpoint-dependent feature-based representations as a secondary description which are applied to the shape decomposition. In this approach the user interacts with the system through different interfaces: Geometric Model Interface, Feature Definition Interface, and Design with Features Interface. The Design with Features Interface allows the designer to create a feature-based model for a given context, through the use of a library of feature descriptions created by the Feature Definition Interface. This approach is similar to the others in terms of its deficiencies in that it has not the capability to handle complex features nor the ability to extract adequate information about the features.

The above discussion has indicated the necessity for developing a satisfactory technique for automated feature recognition. This chapter illustrates a research technique that overcomes almost all of the problems mentioned above. Before going into further details about the structure and theory of operation, it is important to introduce more information about *Features*, in terms of terminology, definitions, types and applications.

4.2 Feature Terminology

Features originate in the reasoning processes used in various design, analysis, manufacturing activities and are frequently strongly associated with a particular application domain. Hence there are many different definitions for features. Some definitions are related to the representation and recognition methodology such as Henderson et al (1990): "Features are defined as geometric and topological patterns of interest in a part model which represent high level entities useful in part analysis". In the design process, a feature is considered by designers as a 'design feature', in terms of its geometry, specifications and details to fulfil certain functional requirements, and thus is sometimes called a 'functional feature'. Examples of such features are fixing holes, keyways and slots as shown in figure (4.1).

Features may be viewed differently by process planners or NC programmers as 'manufacturing features'. For example, a fixing hole may be considered as a drilled or bored hole; a slot may be considered as a general slot machined by a slot cutter. In a metal cutting, a feature may be considered as the volume of material to be removed or a 'volumetric feature' which is of a negative nature, whilst for injection moulding or casting, a feature is usually considered as the volume to be added and therefore is of a positive nature. When the geometry of a feature is being considered, a feature is usually called a form feature.

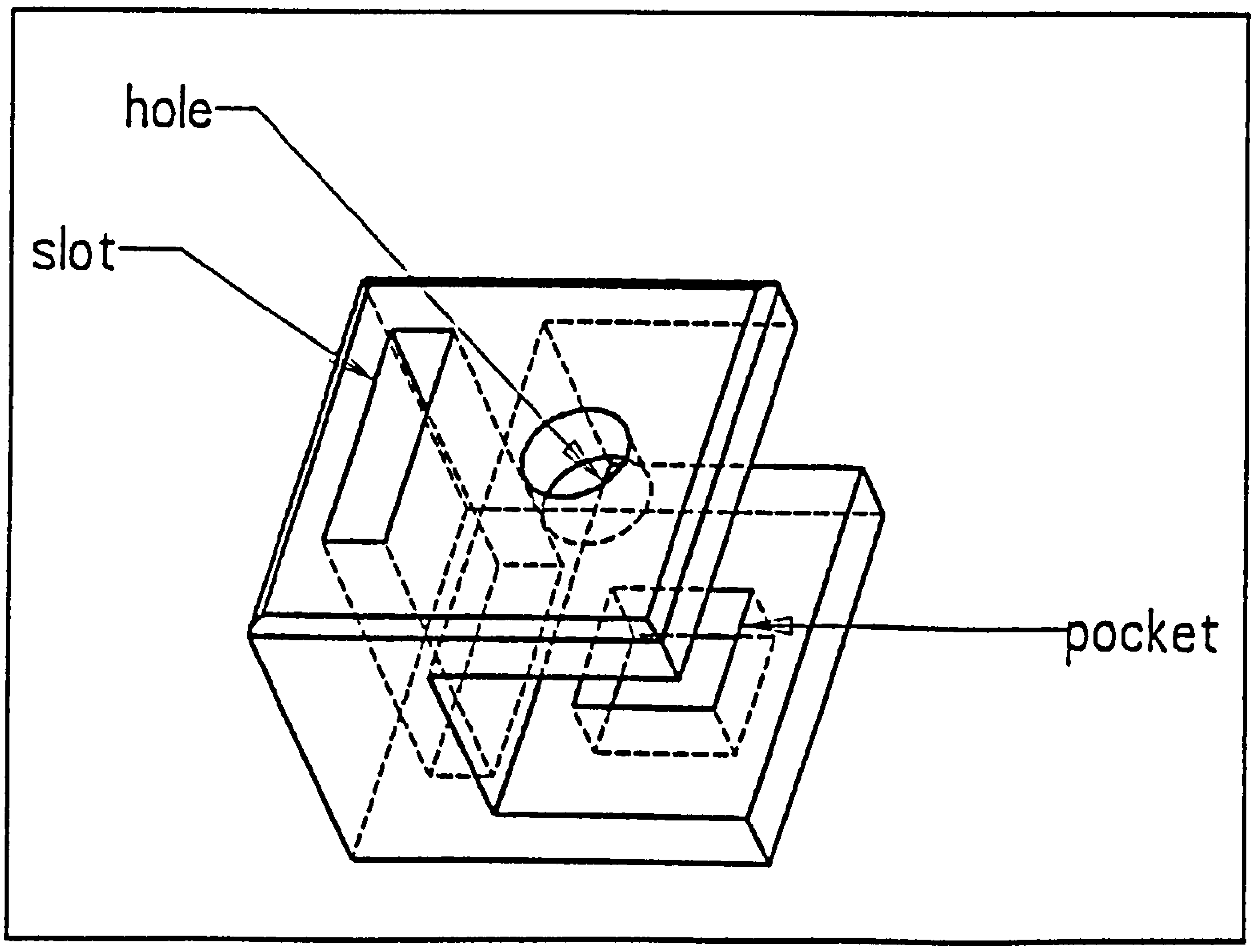


Figure (4.1) An Object and its Form Features

Form features can be classified into three main categories: sheet features, non-rotational (prismatic) features and rotational features. Sheet features are further classified as flat or formed (flat patterns are further classified as depressions, edges, etc., and formed features are further classified as localised and non-localised); non-rotational features are classified as depressions, protrusions and surfaces (Depressions can be internal, external, through and non-through). This research focuses on the primitive rotational features which can be classified as concentric and non-concentric features as shown in figure (4.2). Concentric-features are rotational features whose axis of rotation coincides with the primary axis of rotation of the part. Non-concentric features are rotational features whose primary axes of rotation are different from, and non-coincidental with the primary axis of rotation of the part. On the other hand, concentric-features can be classified into external-features and internal-features. Internal-concentric features such as holes, pockets, and slots could have internal-faces, internal grooves, and internal diameter.

4.3 Form Feature definitions

A feature is an entity or geometric form, its attributes (dimensions, and shape) are very important amongst others industrial functional analysis, evaluation, process planning. The feature attributes must be represented explicitly in terms of forms which match available manufacturing knowledge. Form features such as holes, slots, cuts, rounds, notches, etc., have been given various definitions according to their intended usage. For example, Wierda (1991) gave a very general definition for a feature; he defined it as "a partial form or a product characteristic that is considered as a unit and that has a semantic meaning" in various engineering schemes such as process selection, manufacture, machining cost estimation, product and process design.

Chung et al (1988) have defined features as objects which may contain methods for geometry abstraction, geometric constraints, methods for geometry creation and modification, methods for manufacturing, analysis, assembly, and inherited properties. They proposed a prototype system which provides designers with a set of standard primitive features such as blocks, cylinders, pyramids, full/partial torus, cones/truncated cones, full/partial tubes, and straight/circular fillets. These primitives are represented as an object class in an object-oriented programming methodology. These classes "contain attributes which describe the characteristics and behaviours of its members".

Other authors defined features in two ways; first is called boundary representation while features can be defined in terms of a set of edges, faces and vertices; the second is called

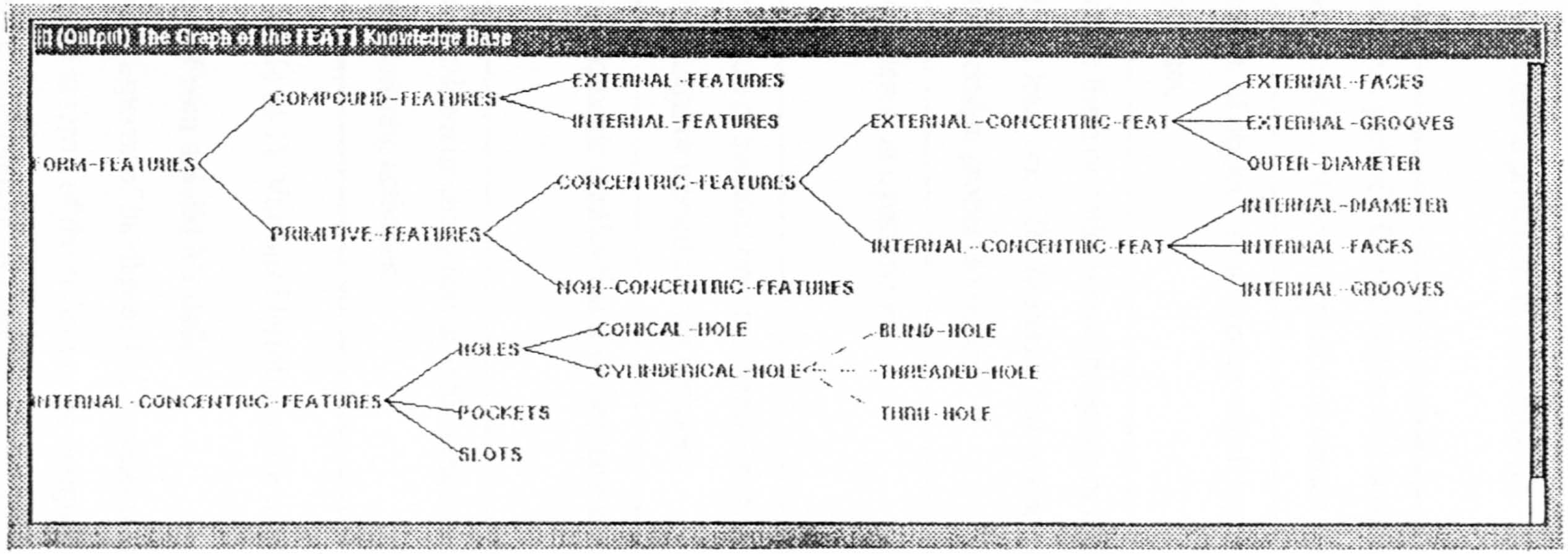


Figure (4.2) Features representation in hierarchy constructive solid geometry and is specified as a set of primitive volumes, cylinders, cones, blocks, spheres, and pyramids, Hummel and Brooks (1986) and Luby et al (1986). Further feature definitions as is described by various authors are listed in table (4.1). More information about form features is presented in Appendix (I).

A form feature is generally a part of a formed object that is physically differentiable from the rest of the object and performs certain functions.	Gadh et al (1989)
A feature is a classification of object characteristics which have significance in some domain.	Hummel and Brown (1989)
A feature is any geometric form or entity whose presence or dimensions are required to perform at least one CIM function, and whose availability as a primitive permits the design process to occur.	Luby et al (1986)
A feature is a region of interest in a part model	Wilson and Pratt (1988)
A Feature is usually a group of surfaces on a mechanical part which have certain meanings to the design or manufacturing activities.	Dong and Wozny (1990)
A feature is a group of geometric entities that together have some higher-level meaning.	Lenan and Mu (1993)
A feature is any geometric form or entity that is used in reasoning in one or more design or manufacturing activities.	Cunningham and Dixon (1988)

Table (4.1) Various Definitions for a Feature

4.4 Feature-Recognition From a Solid Modeller

In this work key research aspects of intelligent CAD systems are addressed. These aspects include representing design in terms of the artifact to be designed and the design process itself in a concurrent engineering environment. A feature-based approach has been developed since a design feature can be a powerful representation and reasoning tool of design. In the feature based design, an artifact is represented by a set of design features and their relationships. Establishing a formal representation scheme was essential for addressing the aspects of feature-based design in a logical and systematic manner. Originating a feature taxonomy was a crucial task for enhancing the proposed feature-based design system. This approach does not depend on a specific design domain, it can be applied to a wide range of design practices. It has also the capability to extract the necessary topological and geometrical information from the solid modeller in an effective and efficient manner. Other information such as the relationships between features are essential for the manufacturing processes. For instance if the part has two holes, it is very important from the manufacturing process perspective to define whether they are crossing or intersecting as shown in figure (4.3a). It is also necessary to indicate the location of the feature on the part for fixturing purpose, particularly if the feature has to be located on a certain slope angle from one of the geometry surfaces or edges, figure (4.3b).

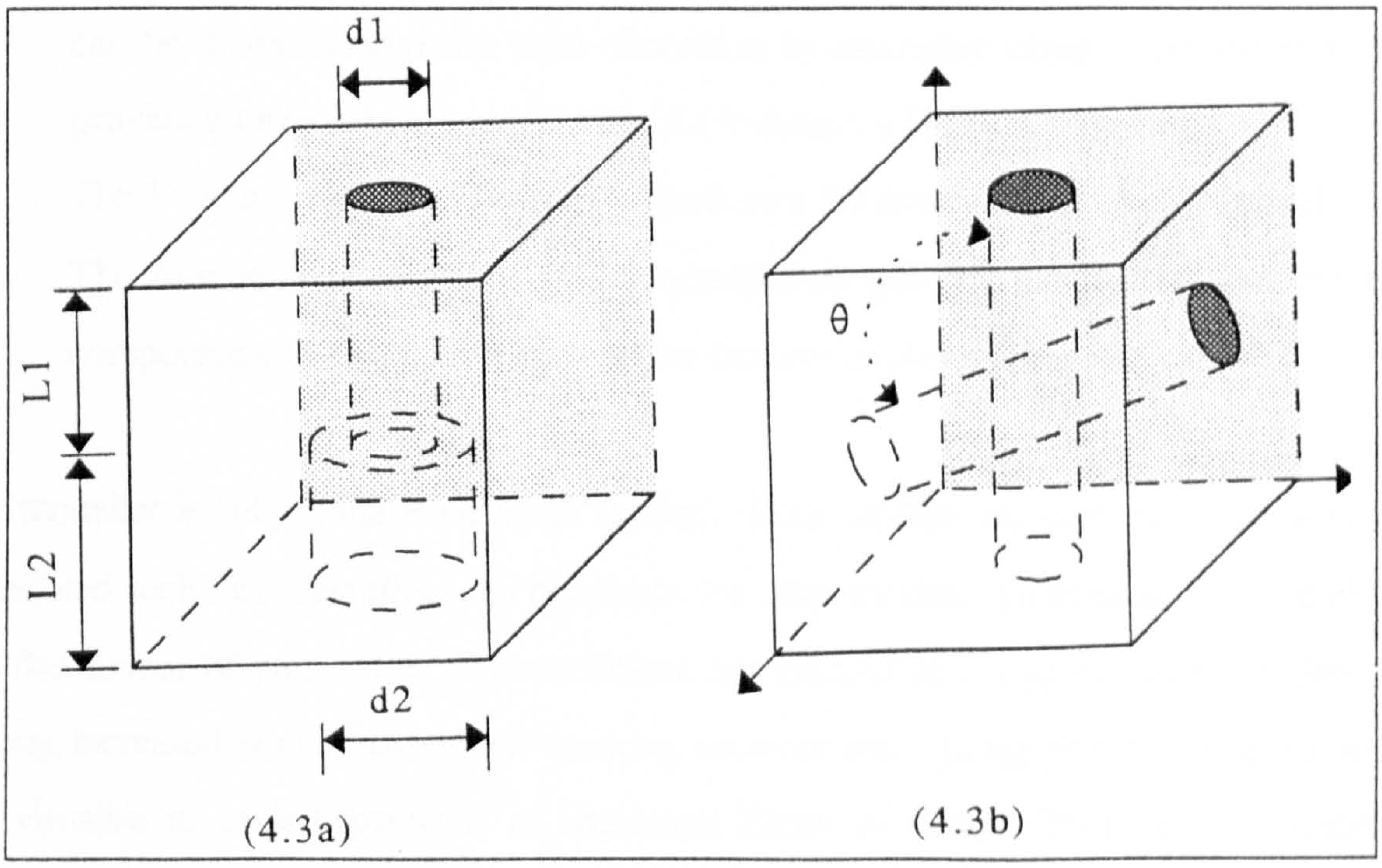


Figure (4.3) Relations between Features

4.4.1 Solid Models

The advent of solid modellers has given engineers greater visual awareness of products, other than by the creation of prototypes, than had been previously available. The construction of a 'view from anywhere' model gives greater scope for considering the various options within the design before the submission of the concepts to mathematical tests, or indeed to the ultimate tests of production and use of the product. The factor that makes all of this possible is that, in the modeller each part is an entity. The design is no longer a collection of lines on a piece of paper, it is a definable entity with definable attributes. The control of these attributes gives the modeller the ability to create a true representation of the part in a very quick manner.

In this research the solid modelling system Pro/Engineer (1991) was chosen. The reasons for choice it being its availability in a research environment together with the facilities which this particular package provides (Appendix II). There are four main modes of operations within this modeller:

- The 'part mode' is the section in which a single component can be manipulated. Features can be added, modified or removed at this point.
- The 'sketcher' provides a method for the creation of two dimensional shapes. These can be projected into the third dimension by sweeping along a defined path, thus providing three dimensional features for inclusion within a component.
- The 'Drawing mode' can be used to produce a 2D drawing from the 3D model.
- The 'Assembly mode' can be used to combine components in a manner such that each component can be added relative to the features of the existing assembly.

The modeller is fully parametric in all modes. Relationships between dimensions can be formulated such that their effect can be seen in the other modes. To summarise it can be said that the advent of parametric solid modellers has created new opportunities for designers seeking increased control over their working environment. Being able to change a design and visualise it, as it happens is an important factor of design. There are a number of techniques for Solid Model construction, the most well known schemes are:

- Constructive Solid Geometry (CSG)
- Pure Primitive Instancing
- Boundary Representation (B-rep)
- Cell Decomposition
- Spatial Occupancy Enumeration
- Sweeping

In this research a combination of both CSG and B-rep were implemented to enhance the system. The following section illustrates the interface to the solid modeller.

4.4.2 The Interface to the Solid Modeller

To enable the construction of an interactive design process the modeller used must provide sufficient external interface capabilities to allow both the modeller and an external program to be able to act together in a unified manner. The programmatic interface (Pro/Develop) to Pro/Engineer, provided by the vendor PTC Pro/Engineer (1991) to enable users to interact with the Pro/Engineer Database, was implemented to enhance the Pro/Engineer user interface. A schematic diagram of the communication methods between Pro/Engineer and *Foreign Programs* is shown in figure (4.4). Two interprocess communication channels were implemented to facilitate the interaction between Pro/Engineer and Foreign Programs (User Code). The protocol PIPE is required in the case of developing an application using Pro/Engineer and Pro/Develop running on the same machine. Otherwise, the protocol RPC (Remote Procedure Control) has to be implemented.

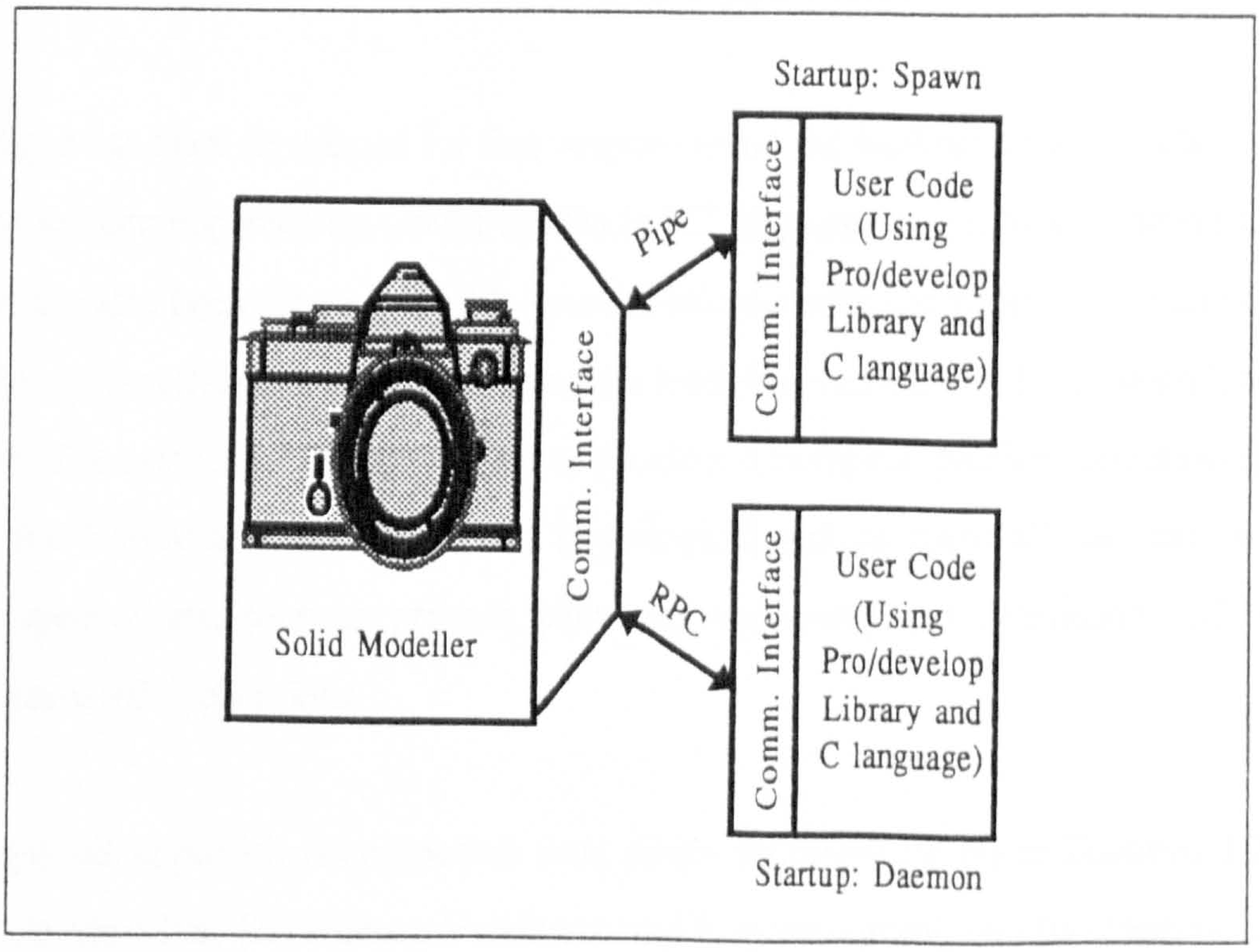


Figure (4.4) An Interface between the Solid Modeller and Foreign Programs

The above enhancement allows software developers to customise and/or create new applications which can be integrated into the Pro/Engineer environment. The above development together with Pro/Develop have been used to expand the functionality of Pro/Engineer by extending its capabilities with user defined applications codes. It has also been used as a mechanism for integrating proprietary applications with Pro/Engineer, and presenting end users with a common user interface. Direct access, to perform specialist engineering functions on the Pro/Engineer database from the available Pro/Develop facilities, is technically not achievable. The approach to overcome these technical difficulties was to use the Pro/Develop library together with codes written in C language in UNIX environment.

4.4.3 The Proposed Approach for Feature Recognition (Feature Recogniser)

As has been previously stated a solid modeller provides a very difficult environment to derive applications such as process planning, machining cost estimation or manufacturability evaluation because the information required for such tasks is not available within the solid model database. In addition, entities on which process planning is based, for example form features, require a higher level of abstraction than that which is available. To achieve the concept of Design to Cost or Design for Manufacturability a comprehensive information set about form features has to be extracted from the solid modeller.

A technique has been developed for that purpose using the facilities of the functions library of Pro/Develop accompanied by Codes written in 'C' language in a UNIX environment. A user interface has also been set up to enable users to interact with the system easily and effectively. Using this system the designer is able to create form features such as holes, round, fillet, slots, and draft. The system has been designed to produce a complete product definition such as the type of the feature and the dimensions (topological and geometrical) that can be used for various applications, such as process planning, machining cost estimation and by several other automated applications.

The proposed approach encompasses four major modules; (i) Form Features Library; (ii) Geometric Modeller; (iii) Feature Validation and Representation; and (iv) Feature Instance & Relation Data, as shown in Figure (4.5). This approach is developed and linked with a reasoning system to identify and check the validity of each feature as well as to perform other applications. Further information about the integration is demonstrated in the following

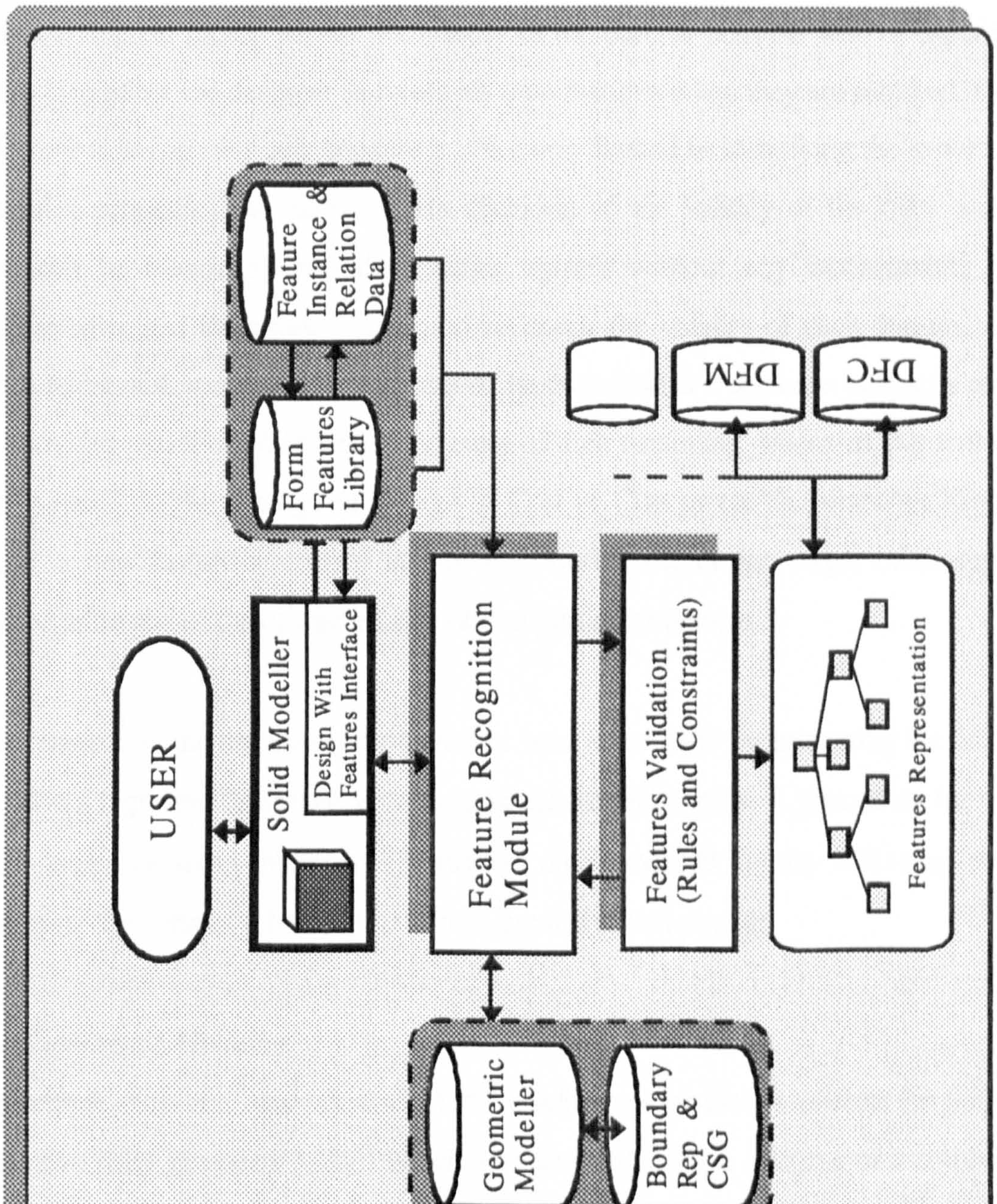


Fig. (4.5) The Architecture for Automated Feature Recognition.

chapters. The structure of each of the above modules is discussed in more detail in the following sections:

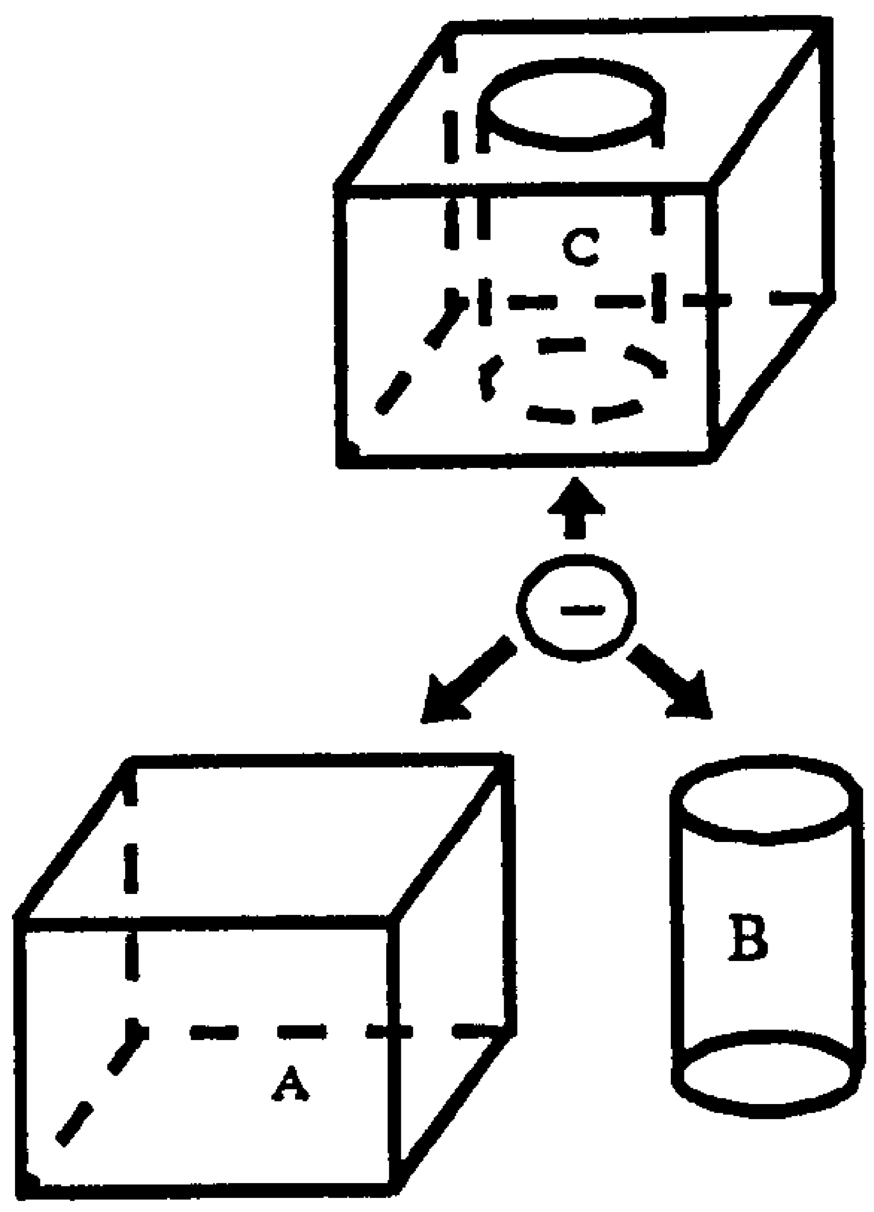
4.4.3.1 *Form Features Library using User-defined Features*

One of the problems with design by features is that the number and forms of the features are infinite and depend mainly on the complexity of the part. A possible way of expediting this problem is to allow the designer to create his own features when they are required. Defining a new feature is not an easy task because it is not only limited to identifying the topological and geometrical properties but also requires checking of the validity of the rules so the new feature can be integrated into the existing system without any inconsistency problem. Cognition rules and inheritance are used to check the validity of each feature. A further problem addressed was that a feature should be described in a common language among the other activities which use features as the basis of their reasoning processes, particularly if the design is based on the strategy of Design to Cost or Concurrent/Simultaneous Engineering. Thus, if a new feature is created at any level during the design stage, other applications should be informed of the characteristics of that particular feature.

In this research work the above problem has been overcome by extracting the information required in a high level language which is readable to all systems. A procedure for creating a feature geometry using parametric formulae are presented in the following section to demonstrate the various schemes that can be applied in this domain.

4.4.3.2 *Geometric Modeller*

The approach proposed here is a dual solid modeller representation scheme; the first is called constructive solid geometry (CSG) which represents objectives in terms of a combination of primitive volumes such as cylinders, spheres, blocks, and tubes as shown in Figure (4.6a). The second is boundary representation (B-rep) which represents models in terms of topology entities such as, loops, faces, edges, and vertices which are associated with geometric entities such as curves, surfaces, and points Figure (4.6b). In the latter scheme objects are represented by their enclosing surfaces. The following section explains the implemented method for creating Geometry.



C = (A - B)

Figure (4.6a) CSG Scheme

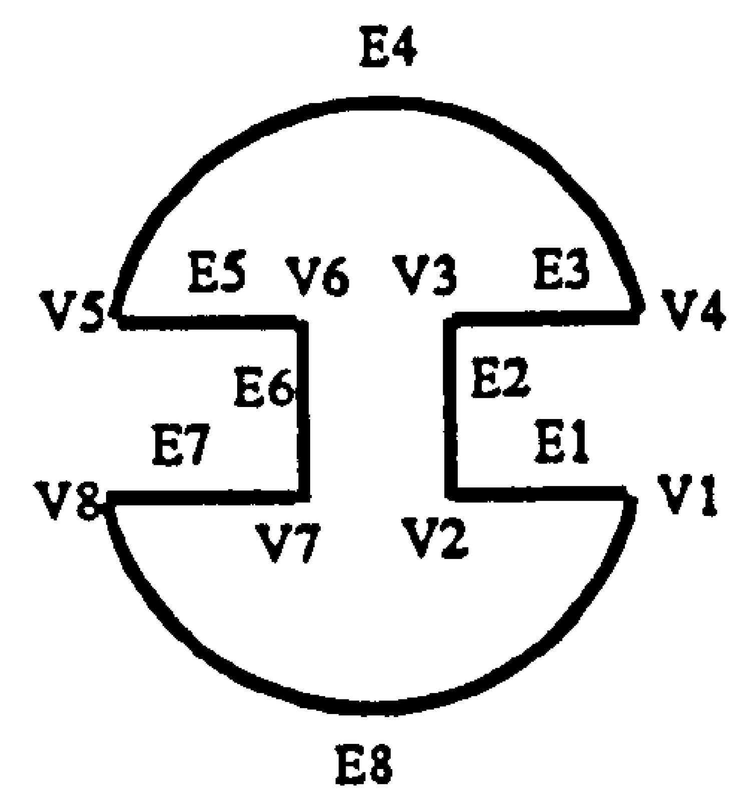


Figure (4.6b) B-Rep Scheme

4.4.3.3 *Creating Geometry*

A surface structure of a Geometry is described by defining the complete information about the boundary of the surface along with the primitive surface which it exists on. The surface boundary of an object is composed of closed loops of edges, each edge is an intersection of two surfaces or contours. The primitive surface is a three dimensional Geometric surface parametrized by two variables, (u , v). In this section techniques for generating samples of various types of features are presented. For instance, a hole or a shaft which is considered as a form feature, and the cylindrical face of this type of feature is created from a line parallel to the axis and at a constant distance from the axis. In the case of a cone the line is inclined with an angle "θ" to the axis of rotation, and the radius of the cone is function in (v,θ). The height of either the hole, shaft, or the cone is the vertical distance from the bottom face to the top face "v". Figure (4.7) shows a cylindrical feature and the parametric formula for creating this type of feature which could be a shaft or a hole as it is described below.

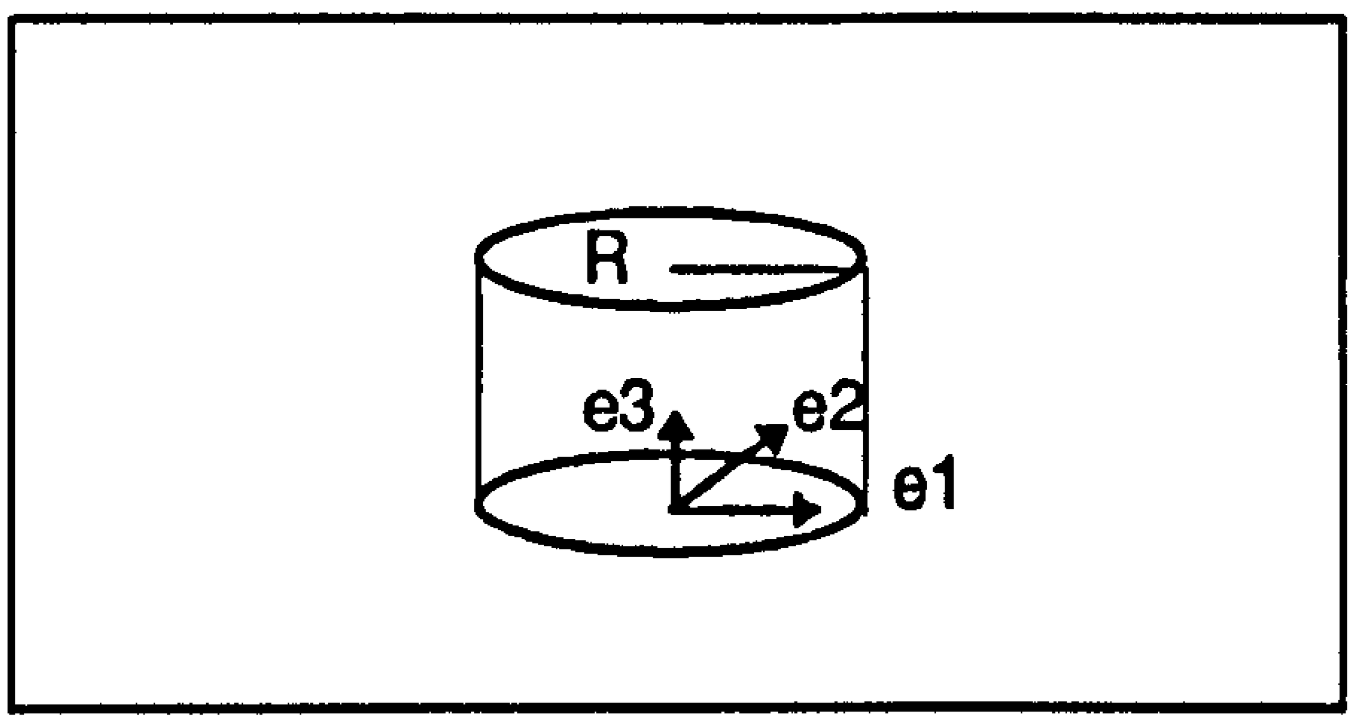
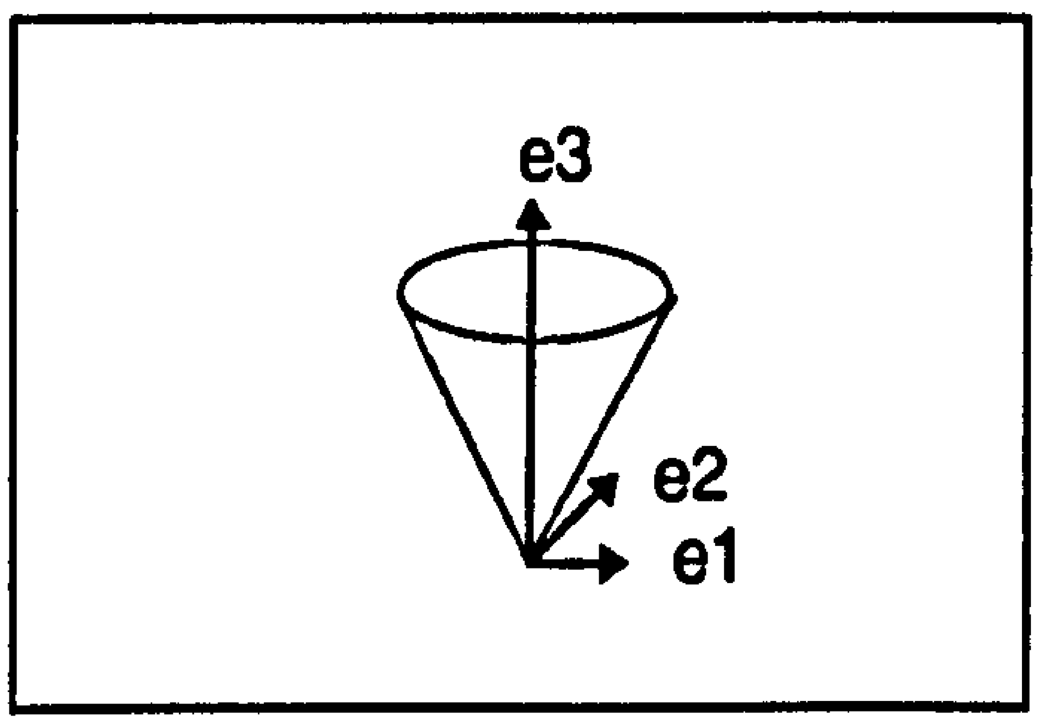


Figure (4.7) A Cylindrical Feature

(x,y,z) = f (radius, u, e1, e2) + f (v, e3) + f (origin)

(x,y,z) = (Origin points) + [e2*sin (u)+e1* cos (u)] * Radius + e3 * v

In the case of a cone (Figure 4.8) the above formula is applied with considering the radius as a function in (v,θ). Where θ is the angle between the axis of the cone and the generating line (PTC 1991).



R = v * tan (θ)

Figure (4.8) A Conical Feature

A feature in this context is a term used to define the characteristics of a part. A feature can be created by removing (eg. slot) or adding (eg. protrusion) material to the part. In the logic program a set of functions were used to identify features. The function "prodb_first_udf" was used to get the “id” of the first user defined feature. While prodb_next_udf gets the next feature. In the udf library, features are classified into groups, a feature from a specific group should have its group's name, and to get the name of a particular feature the function "prodb_get_udf_name" must be used for that purpose.Other functions "prodb_first_dim_udf" and "prodb_next_dim_udf" were used to get the "id" for the first and second dimension of the feature. The function "prodb_place_udf" is used to place the user defined feature on a part using the specified dimension values in the "place_data" array. The flow chart of the code which has been written for a hole is shown in figure (4.9a - 4.9e). A sample of the program is presented in figure (4.9f).

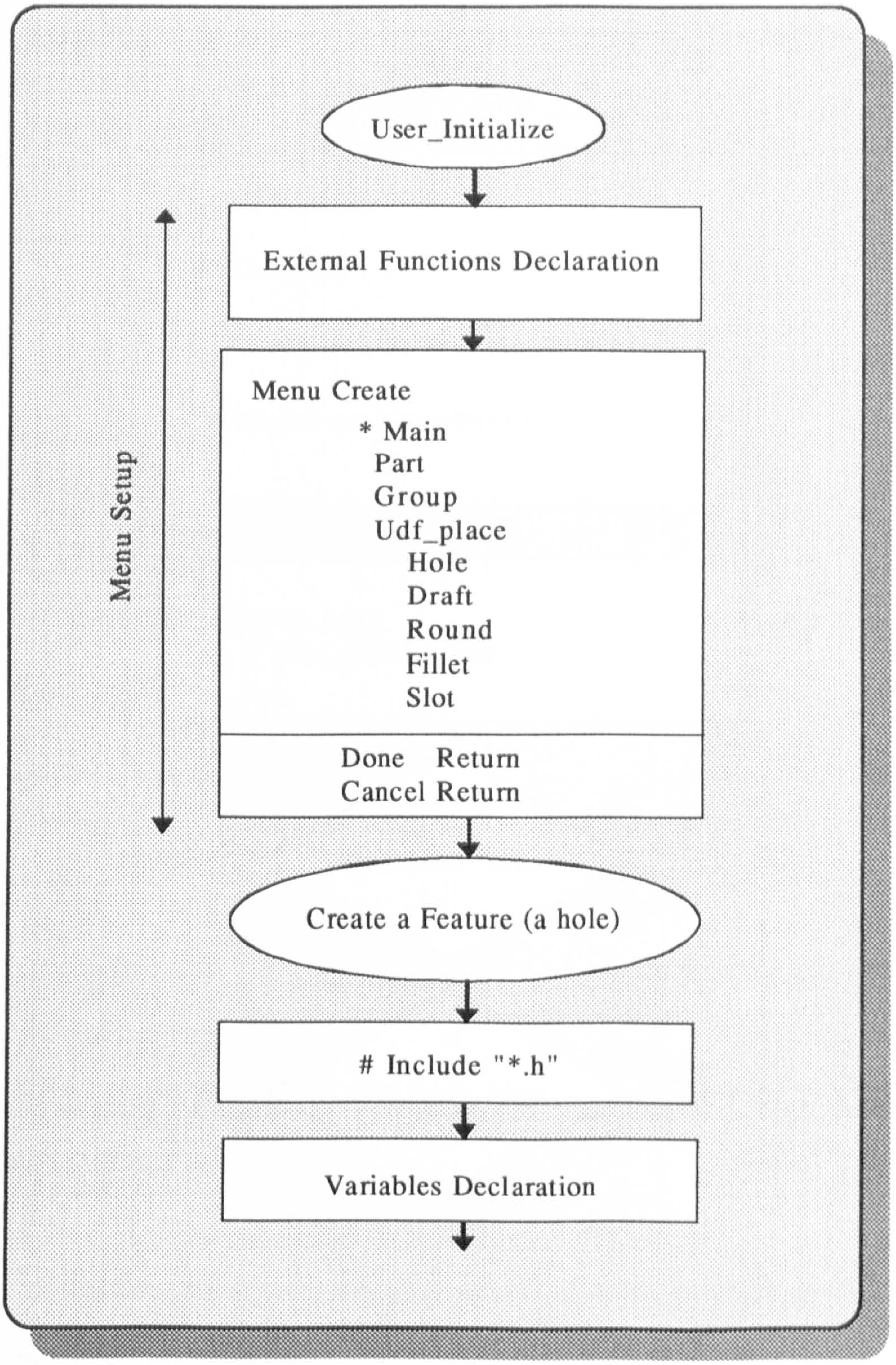


Figure (4.9a) Flow Chart of a Feature Creation and Extraction

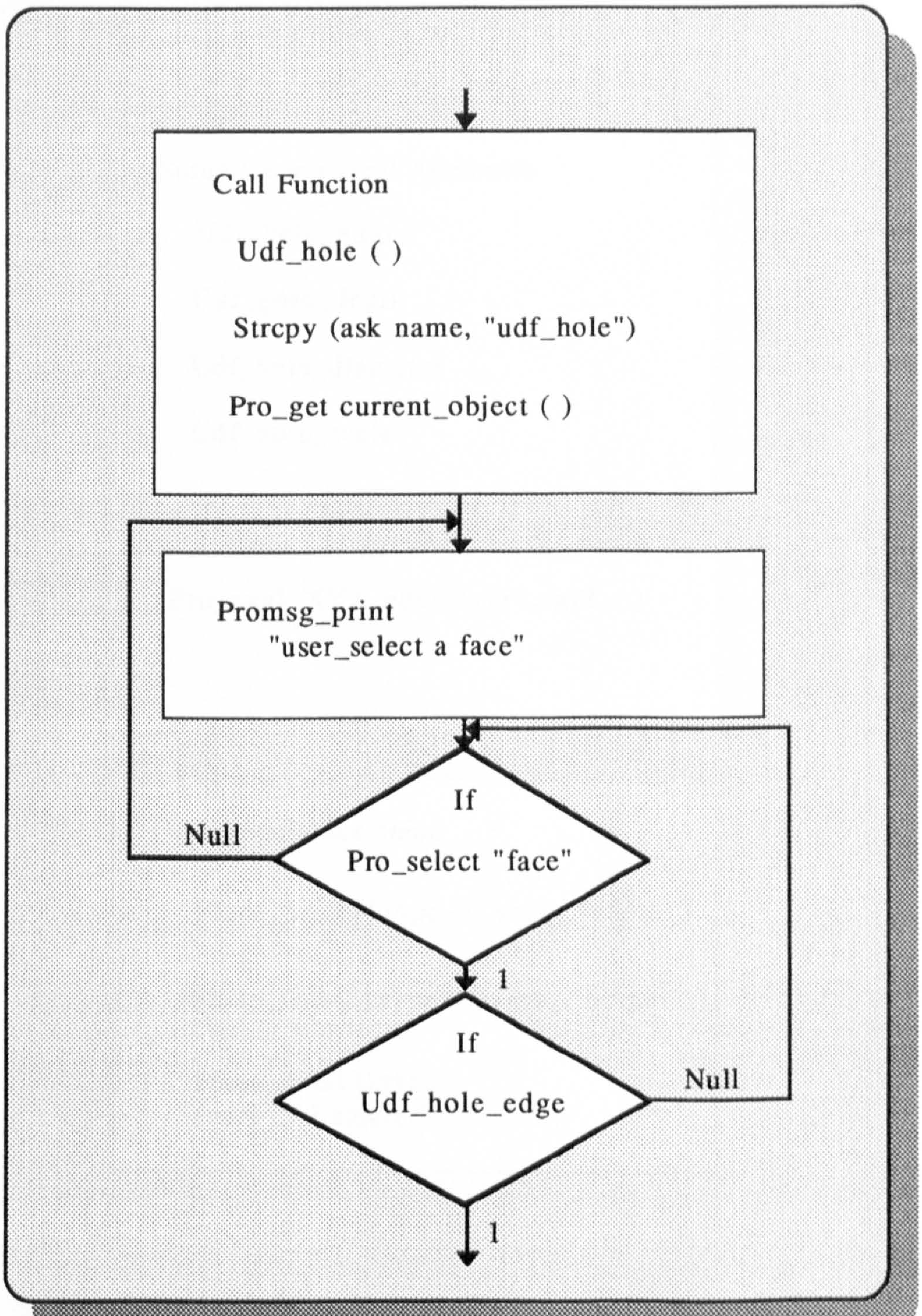


Figure (4.9b) Flow Chart of a Feature Creation and Extraction

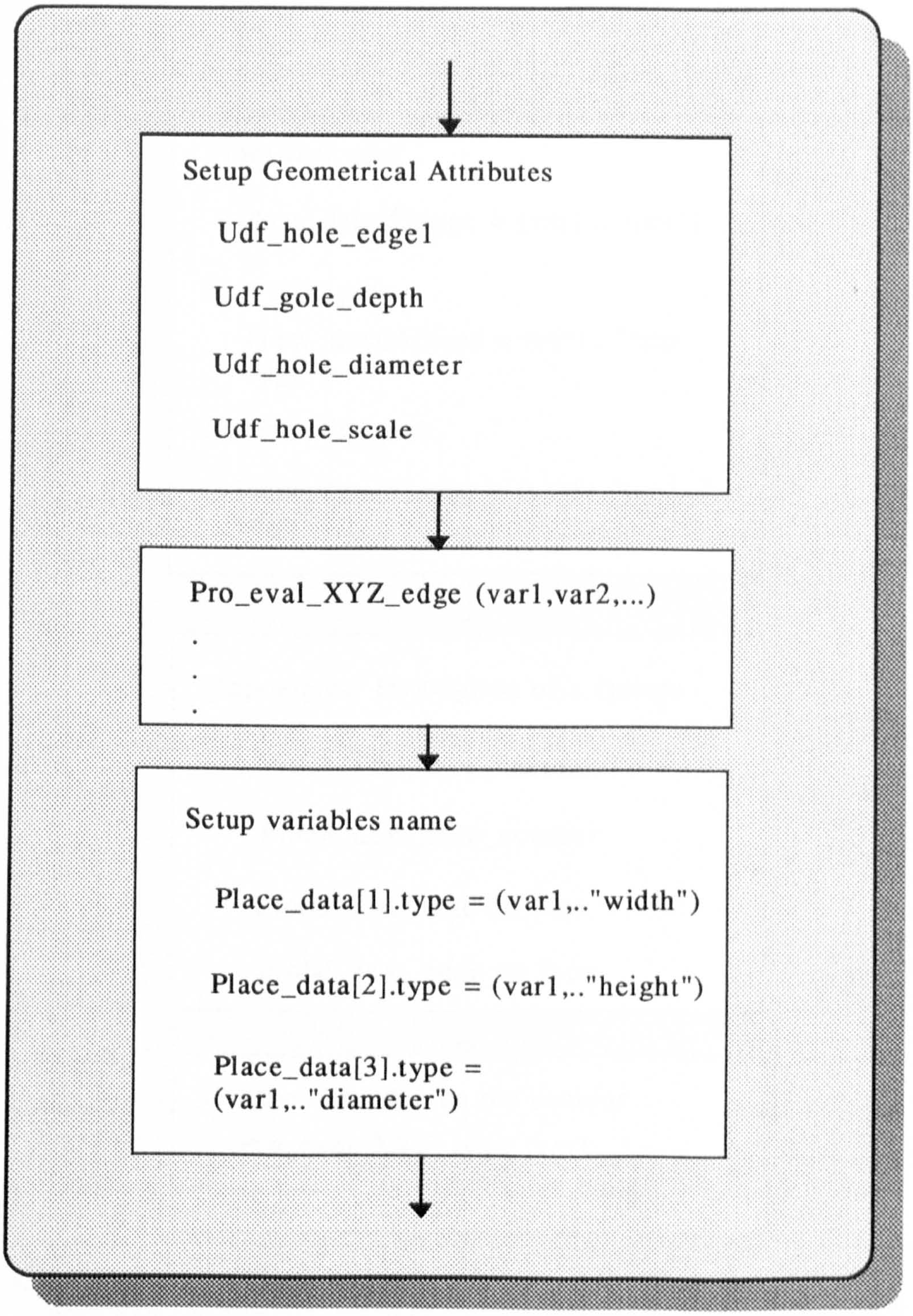


Figure (4.9c) Flow Chart of a Feature Creation and Extraction

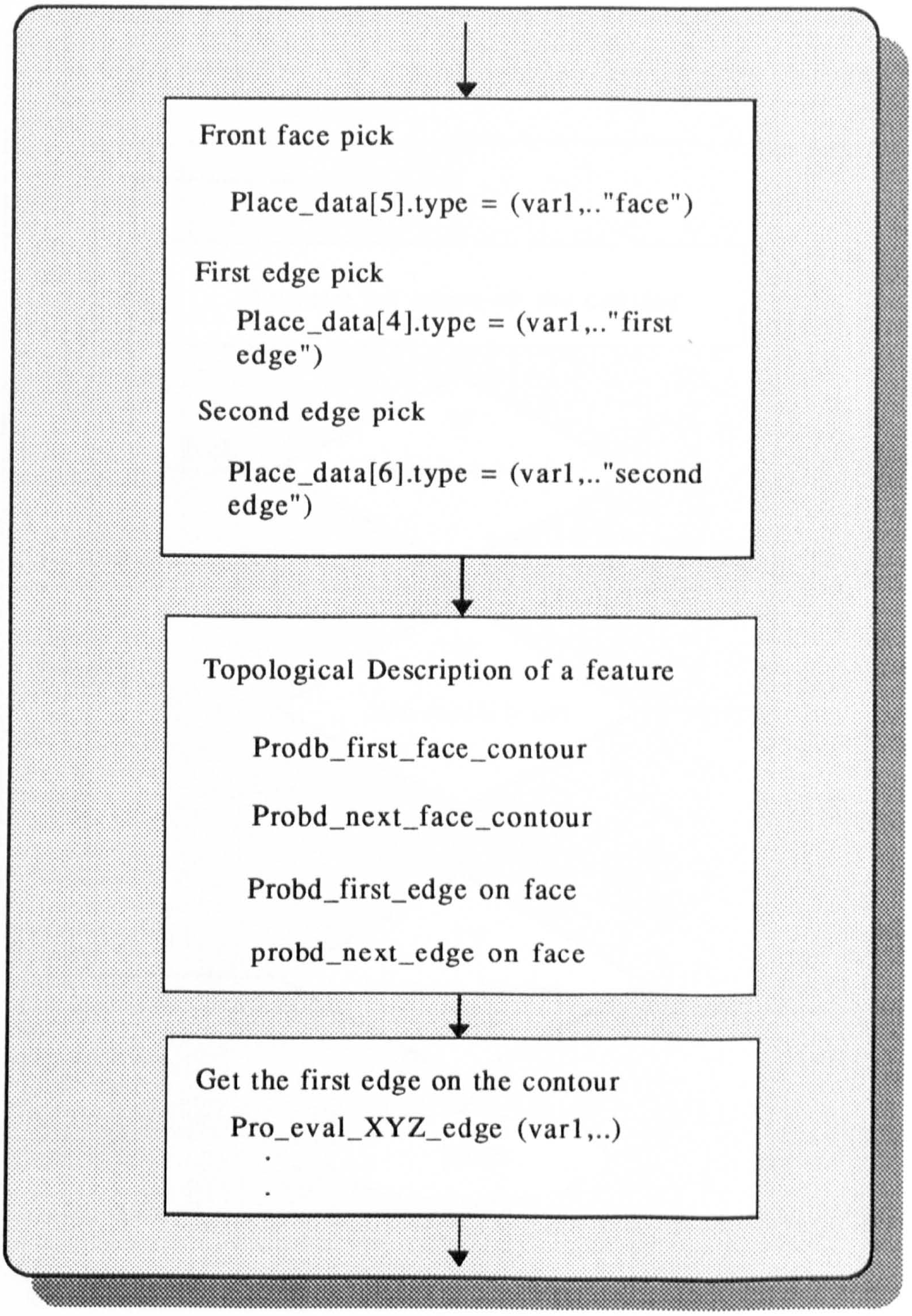


Figure (4.9d) Flow Chart of a Feature Creation and Extraction

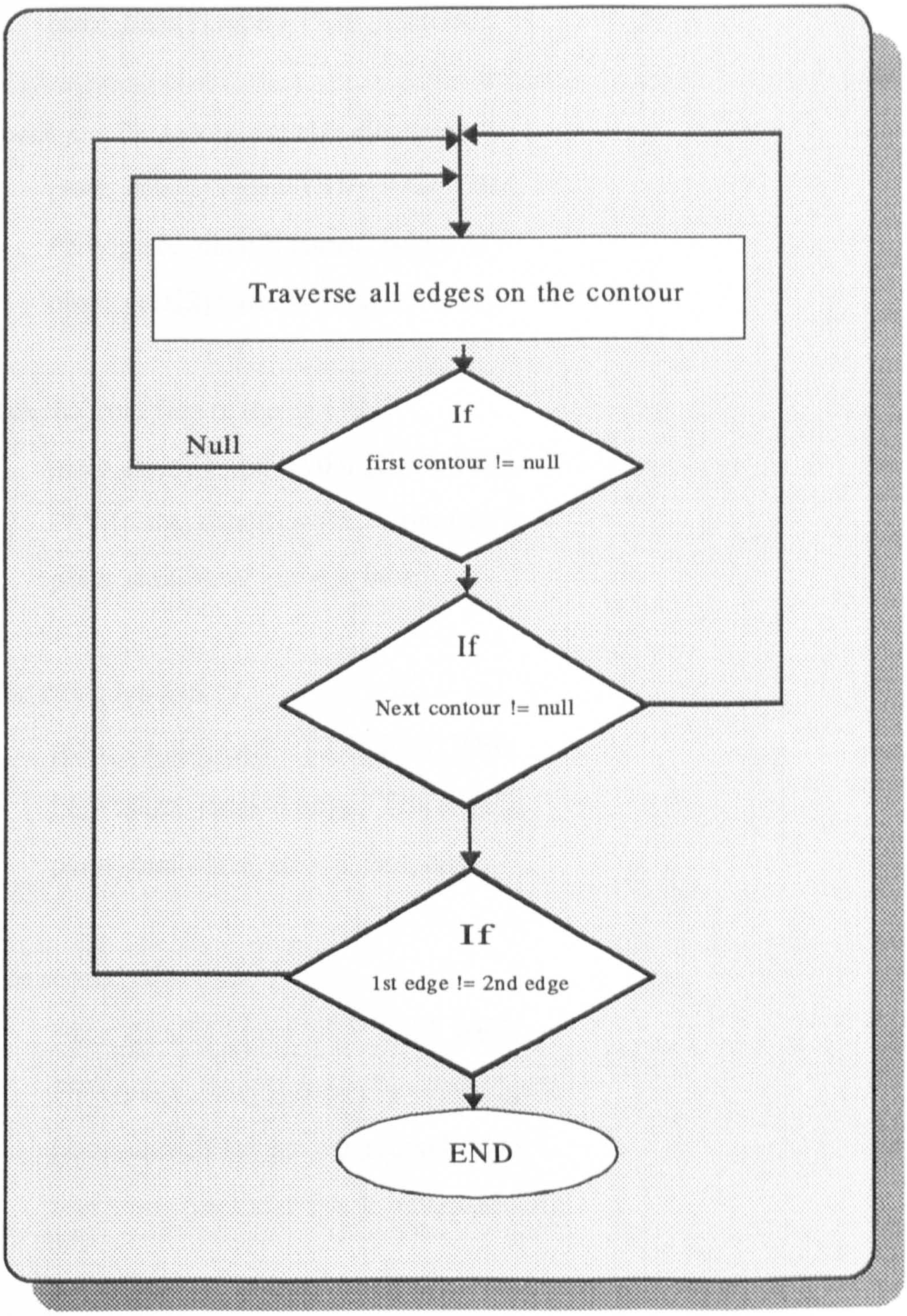


Figure (4.9e) Flow Chart of a Feature Creation and Extraction

```
/* Specifying the first variable dimension */
place_data[0].type = UDF_VAR_DIM;
        PSW(place_data[0].name, "width");
        place_data[0].value = dist1;
        place_data[1].type = UDF_IGNORE;

/* Specifying the second variable dimension */
        place_data[2].type = UDF_VAR_DIM;
        PSW(place_data[2].name, "height");
        place_data[2].value = dist2;

/* Pick the front face of the part */
        place_data[3].type = UDF_EXT_REF;
        PSW(place_data[3].name, "front face");
        place_data[3].ref_ptr = p_face;

/* The first edge pick */
        place_data[4].type = UDF_EXT_REF;
        PSW(place_data[4].name, "first edge");
        place_data[4].ref_ptr = p_first_edge;

/* The second edge pick */
        place_data[5].type = UDF_EXT_REF;
        PSW(place_data[5].name, "second edge");
        place_data[5].ref_ptr = p_second_edge;
        user_copy_vector(udf_hole_pnt,quadrant);

/* Quadrant pick */
        place_data[6].type = UDF_VAR_PNT;
        PSW(place_data[6].name, "width");
        place_data[6].ref_ptr = (char *)quadrant;
```

```
/* Specifying the diameter of a Hole */
        place_data[7].type = UDF_VAR_DIM;
        PSW(place_data[7].name, "diameter");
        user_get_scale(SEL_3D_SRF, p_face, &scale, NULL, NULL);
        diameter = 0.05 * scale;
        place_data[7].value = diameter;
        place_data[8].type = UDF_LAST;
```

Figure (4.9f) A Sample of the Hole Creation program

4.4.3.4 *Feature Recognition and Validation*

Feature recognition follows rules of logic. Basically, the system compares the attributes of a new feature with a predefined one. A set of rules have been implemented for recognising the features topologically. For instance, when the conditions of a rule are satisfied then the conditions are valid. So to recognise the type of a form feature, the following approach is being followed;

If < X > Then < Y > ;

while X is the conditions and Y is the conclusions. For example, the recognition of a hole can be defined through the following rules:

If

(There is a circular top edge) and

(There is a circular bottom edge) and

(There is a cylindrical face) and

(There is a top face) and

(There is a bottom face)

Then

(The feature is a hole)

These rules (recursive rules) are used for recognising the feature type (holes, drafts, slots, rounds and fillets) by matching the available feature's data with predefined feature characteristics. After defining all the features, geometrical and topological, the system records and represents them in groups according to their types. The extracted data of a feature is used to determine the proper set of machining operations and set-ups required to produce the part.

In the actual program another condition has to be added to differentiate between a shaft or cylinder and a hole. Two ways were implemented to tackle this problem; first by estimating the total volume of the part , if it is increased that means material has been added then the feature is a cylinder. The second method is comparing the original weight of the part with the final one (after creating the feature) if it is decreased then the feature is a hole.

4.5 System Operation

For recognising a feature, the system starts to find a set of faces and their attributes using the "User-defined Features approach" as discussed below. The system then matches all the collected entities and their characteristics (types of edges and types of faces) with the predefined features for defining the feature topologically. Features such as holes, drafts, slots, and rounds have been defined as recognisable topologic and geometric patterns using the boundary representation scheme. The feature recogniser extracts the feature attributes (depth, diameter, distances, etc.) and then sends it to the reasoning system for representation which can be used for various applications.

4.6 SUMMARY

In this chapter, a technique for recognising and extracting form features from a solid model has been demonstrated. The system has the capability to identify the features topologically and geometrically. The benefits of this are significant in a number of various applications such as process planning, and cost estimation. The proposed technique has been discussed briefly to highlight the advantages and effectiveness of this approach compared with available ones.

CHAPTER 5

AN INTEGRATED KNOWLEDGE-BASED & CAD SYSTEM

5.1 Introduction

This chapter describes a prototype system that uses commercially available toolkit, Knowledge Engineering Environment (KEE) for knowledge representation, interface, Object-Oriented Programming, reasoning about geometry and geometry construction as shown in Figure (5.1). KEE was developed by Intellicorp (1989), and the lisp language was chosen to build this system on a SPARC Station 2, Model: GDM_1662B. The system

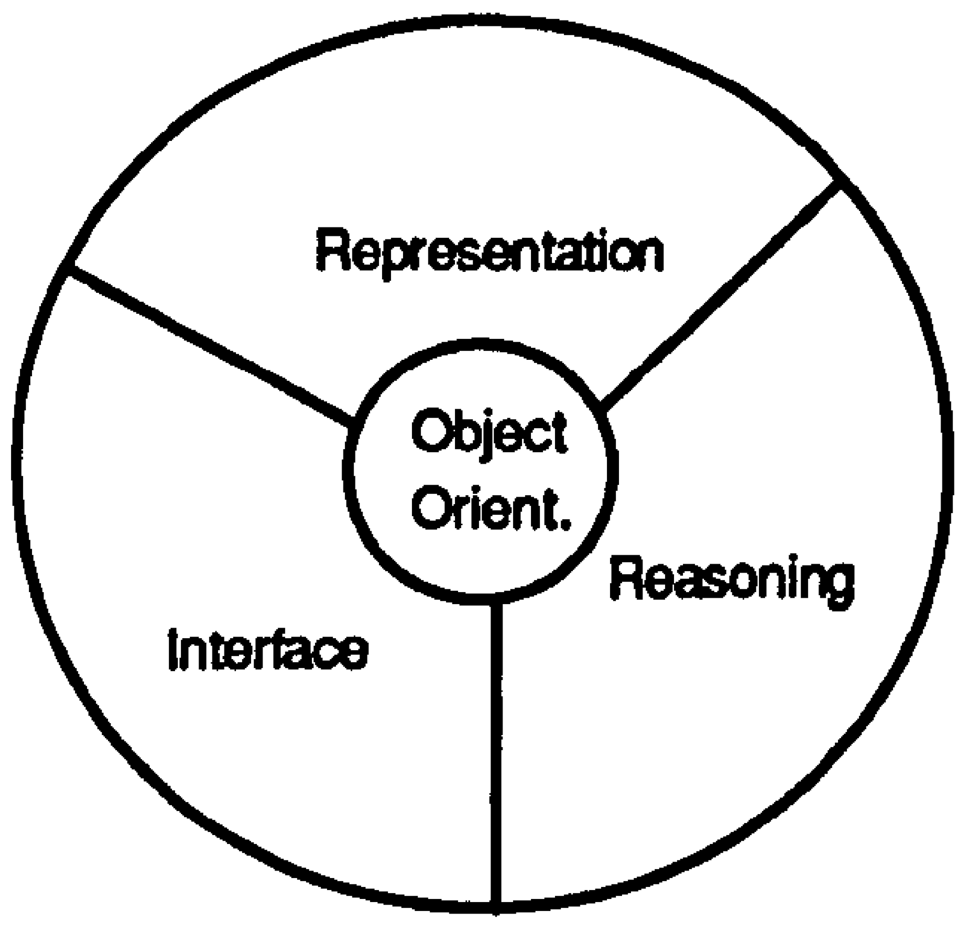


Figure (5.1) The Basic Components of the KBS Toolkit

supports frame-based objected-oriented programming and rule-based reasoning. Each object in KEE is represented as a single frame, called a unit, and each unit is composed of slots. Each slot can contain data or a procedure which describes the characteristics and behaviour of a particular object. The objects in the application domains are represented in a hierarchical class-subclass-member structure. Attributes and methods of a class higher in the hierarchy can be inherited by classes at a lower hierarchy. Relations between applications domain are represented by slots. The member and subclass slots have special significance because of the inheritance mechanism.

This chapter also explores linking the commercial Artificial Intelligence programming environment KEE and the solid modeller (Pro/Engineer) as well as the process planning system ENGIN. The investigation of the necessary links between these tools for geometric reasoning, the data structures required in each environment, and the overall performance and usability for additional application domains as well as areas needing more development on the part of both CAD and AI software vendors.

This chapter is organised as follows, first the overall interface between the different IT tools, system architecture, data and knowledge representation, construction of the Knowledge-based system (KBS), and simulation results are discussed. The intention here is to give a brief demonstration of the system's integration mechanism rather than presenting in detail the sophisticated software programs which have been written to establish this system. The flow charts of the whole process are illustrated in figures (4.9a-4.9e) and figure (5.2) respectively. The latter diagram demonstrates only the protocol which has been developed to accomplish the integration.

5.2 Communication Interface between the Solid Modeller and the Reasoning System

The Knowledge-based System toolkit (KEE) together with the CAD system (Pro/Engineer) were seen as an ideal medium for achieving the goals of this research. Consequently, the integration between the solid modeller and the reasoning system was considered as an essential step for achieving the objectives of this project. KEE itself does not provide an external communication capability but allows complete access to Lucid's Common Lisp language. Common Lisp in turn supports a foreign language interface to communicate with PASCAL, FORTRAN, and C languages. These external languages can then open, read, and write files. On the other hand, Pro/Engineer can communicate to the outside world through the programmatic interface Pro/Develop, as it has been discussed in Chapter (4). The major elements encapsulated in establishing the interface is described in the following sections.

5.2.1 The Connection Mode

The connection mode was constructed using Object-Oriented Modelling or programming which is based on the client and server relationship. A client object sends a request to a server object which interprets the request to decide which operation to perform. A request includes at least parameters to identify the object and the requested operation. The following sections explain how a client establishes a connection to a server and then communicates with it, and the interaction between the two sides (KEE and the CAD system).

The scenario is that the client establishes a connection with a server process, then the server transfers the data to the client, which in turn writes the received data in standard format file. In principle the connection-mode service encompasses four phases:

- *Local Management;*
- *Connection Establishment;*
- *Data Transfer; and*
- *Connection Release.*

The structure and theory of operation of each of the above phases has been described below as follows:

- ***Local Management***

The role of the local management is to identify the local operations between a transport user and a provider. At this stage the transport user has to establish a channel of communication with the transport provider, each channel has a unique endpoint of communication, selecting a channel is supported by the "t-open ( )" routine. In any connection process each of the client and server establishes a local channel to the transport provider and specify its identity using "t_bind ( )" as shown in figure (5.2). Each transport provider has a set of characteristics that determines the types of services and the limits associated with it. These information and limits including:

- maximum size of a transport address;
- maximum message size;
- maximum number of bytes of user data that can be passed between KEE and the Solid Modeller; and
- maximum bytes of protocol-specific options that can be passed between the two sides.

- ***Connection Establishment***

This phase was used to create a virtual circuit or connection between the client and the server. The server apprises some services to KEE, and then listens for its requests, as each client at the solid modeller side requires the services from the server. The connection between both sides is indicated by the routine t_connect ( ). In this protocol the server is notified of each incoming request via the "t_listen ( )" as well as the "t_accept ( )" for accessing client's

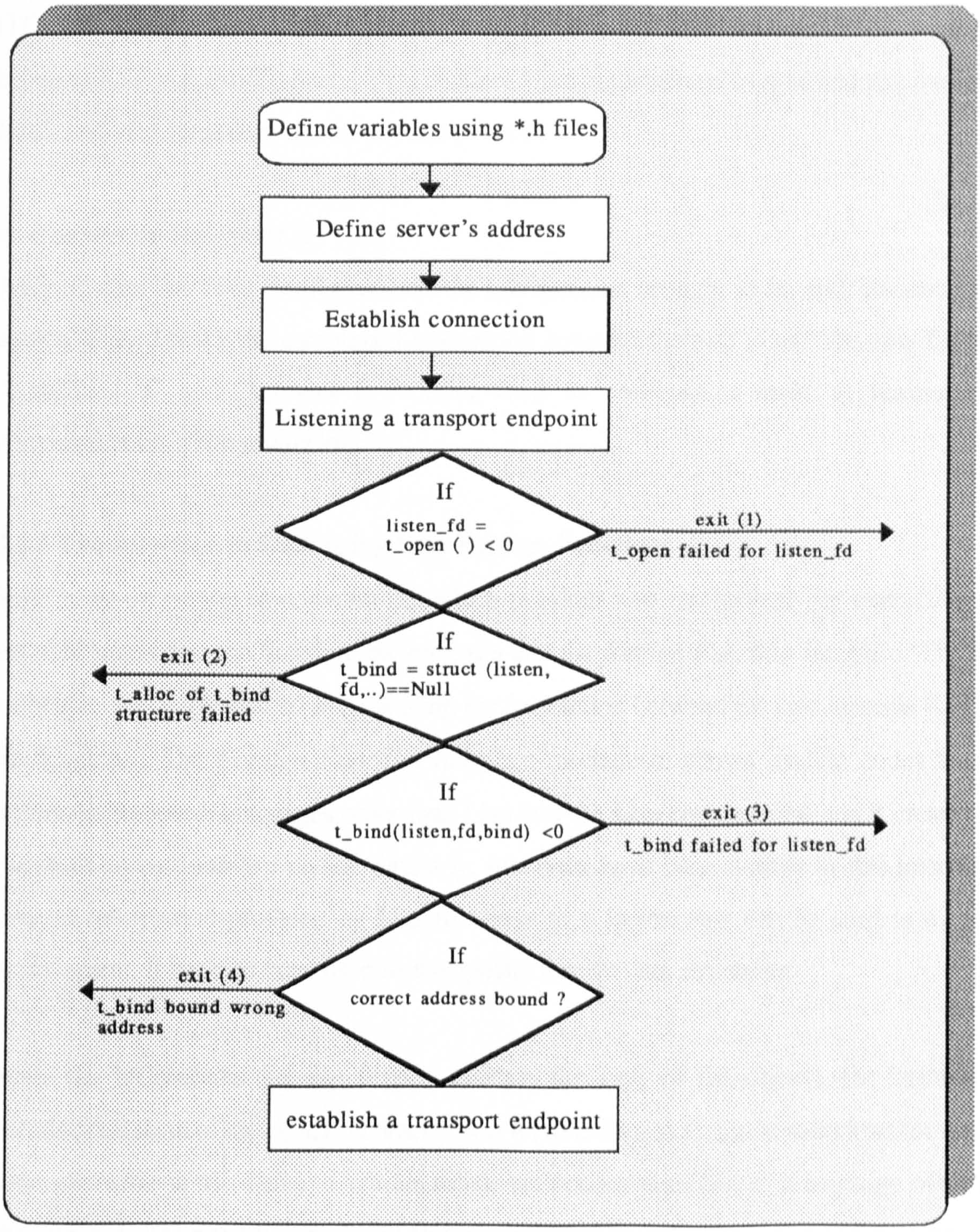


Figure (5.2) Flow Chart of the Local Management Program request to the server. The connection could be established only if the client's request has been accepted by the "t_accept ( )" to be accessed to the server.

- *The Data Transfer (DT)*

DT facilitates the data transfer process in both directions over an established connection between KEE and Pro/Engineer. Two routines were implemented to send and receive data to KEE, and vice versa over the connection process.

- *Connection Release (CR)*

After all data has been transferred and the conversation brought to an end, the connection release phase breaks the established connection between the two sides. The two functions "t_sndrel ( )" and "t_rcvrel ( )" were used to construct a code to terminate the communication without data loss.

5.2.2 The Interface to KEE using Lisp Foreign Functions

KEE is set-up on top of common lisp which provides two mechanisms for interacting with external languages: the function *run-program* and the *foreign Function Interface.* The latter technique was implemented in facilitating the interaction between the two systems KEE and Pro/Engineer. The *Foreign Function Interface* mechanism allows loading codes that are written in computer languages other than Lisp into the Lisp environment, and it creates Lisp functions to call non-lisp codes. Similarly, functions have been written in this interface to convert information provided by Lisp functions to a format that can be used in a foreign environment. It has also been used to manipulate foreign data structures.

Since the bit patterns for lisp objects indicate the type of the objects, for instance the hexadecimal form of the ASCII character A is 4116 in lisp; in C, the hexadecimal form of the same character is 41. Thus, to communicate with codes compiled in a language other than lisp, the lisp data must be converted to a representation or format that other languages can understand. The following are the features that implemented to establish the interaction:

• The lisp functions that call foreign functions (def-foreign-function):

The macro def-foreign-function was used to define a lisp function that calls a foreign function. It copies the Lisp data into foreign space, which is guaranteed to be stationary. After the call is finished, the foreign space is reclaimed. While the macro def-foreign-callable was used to define a lisp function that can be called from foreign code (PTC 1991). A procedure for implementing this function is shown below:

def-foreign-function name-and-options {documentation}*
{*arg-description*}*
[&optional {*arg-description*}$^+$]
[&rest {*arg-description*}$^+$]
[&key {*arg-description*}$^+$]

name-and-options::= *function-name*
| (*function-name* {*option*}*)

option::= (*:language language*)
| (:name *foreign-name*)
| (:return-type *foreign-type*)
| (:max-rest-args *value*)

arg-description::= arg-name
| (*arg-name foreign-type*)
| (*arg-name default-value*) *foreign-type*)

• Lisp functions that are called from foreign functions (def-foreign-callable)

These functions have been used to define a Lisp function that can be called from a function defined by a language other than Lisp. The depiction of this function was described as follows:

def-foreign-callable *name-and-options ({arg-description}*)*
*{declaration / documentation}**
*{form}**

name-and-options::= function-name
/ (function-name {option})*

option::= (:language *language*)

| (:name *foreign-name*)

| (:return-type *return-type*)

arg-description::= (arg-name foreign-type)

- Foreign data structure: this function was used to define the structures within Lisp that are determined by the C language. Each structure was given a fixed number of named components called slots. The structure of this function was demonstrated as follows:

def-foreign-struct *name-and-options* {*slot-description*}*

name-and-options::= structure-name

(*structure-name* (:alignment *alignment-info*))

structure-name::= symbol

alignment-info::= (:modulus *value*) | (:modulus *value* :remainder *value*)

slot-description::= (*slot-name* :type *slot-type-name*)

| (*slot-name* :type *slot-type-name*

:overlays *previous-slot-name*)

| (*slot-name* :type *slot-type-name*

:offest *value*)

slot-name::= *symbol*

slot-type-name::= array-element-type-name | field-type-name

array-element-type-name::= *primitive-array-element-type-name*

| *previously-defined-structure-type-name*

| (:array *array-element-type-name*

array-dimension-list [*array-discipline*])

- Dynamic linker for foreign code and librariers

The function *load-foreign-files* loads foreign language compiled files into the running Lisp environment. The function load-foreign-libraries loads selected functions from foreign language library files, files have "*.o" extensions, and libraries have "*.a" extensions.

5.2.3 Working Scenario

To start designing a part the designer has to begin with specifying all the features and dimensions of the model using the CAD system. The designer must also use the enhanced interface "Udf_Menu" to create the necessary features. After creating all the features, the feature recogniser starts to create a database which includes all the topologic and geometric data of the part. This database is accessible to any other programs within or outside this application. For instance, in this particular application a bi-directional channel between both the knowledge-based, the process planning system and the database was set-up to facilitate transferring data between these components.

In a typical scenario, when a request for a geometric data query is received, KEE invokes the proper lisp method which calls the connection mode with a command string as an argument. The connection mode then puts the command string in a disk file and goes into a wait and check cycle until complete information comes back from Pro/Engineer. When the connection mode receives all the data requested back from Pro/Engineer, it terminates the wait and check cycle and sends the data back to KEE through Lisp. KEE then acts on the received data and creates corresponding data structures to store the information for further reasoning, analysis or applications. Figure (5.3) illustrates the Overall System Architecture of the interface between the CAD system and the Knowledge-based system toolkit (KEE), and figure (5.4) shows the developed design environment.

5.3 The Interface to the Process Planning System (ENGIN)

The feature recognition approach was used to facilitate the interface between the integrated CAD & KBS and the process planning system (PPS). The work illustrates in a research sense, as to what is possible using the system. However, many man years of effort are required to cover every possibility. Hence the results demonstrate, in a research manner, the capabilities of the system. For example if the researches available in a project such as CONSENSE (EP 6896, sponsored by the European community Commission) were available then obviously more significant contribution could be made.

In this research the paradigm is developed to illustrate the data transmission procedure between the different components encompassed in the process selection paradigm, as shown in figure (5.5). For generating a process plan for a specific part or feature, the CAPP module starts to interrogate the CAD Database regarding specific information about the attributes of the feature. In the case of irrevocable data the system asks the user to input this data

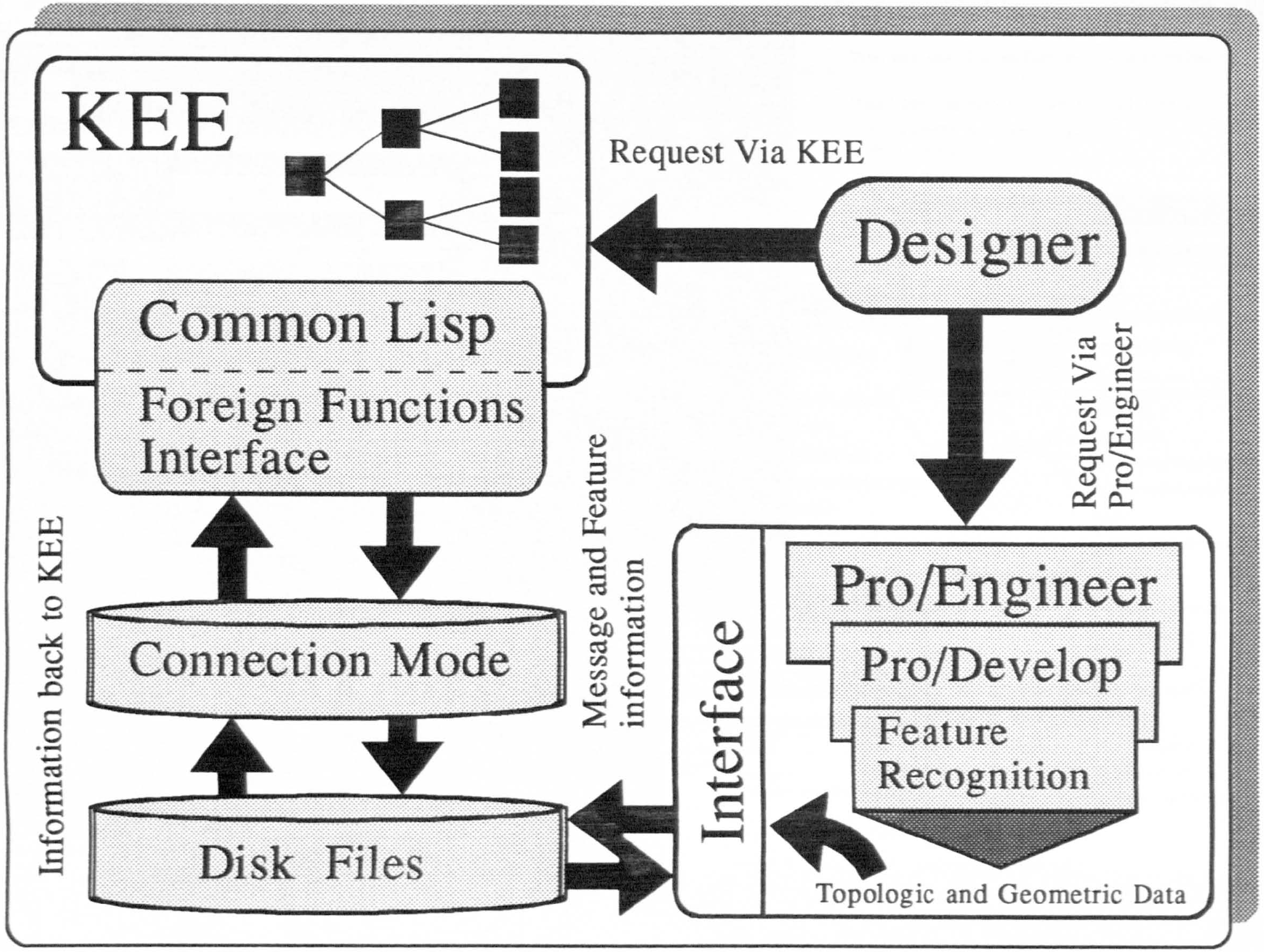


Figure (5.3) The Overall Architecture of Pro/Engineer & KEE Interface Model

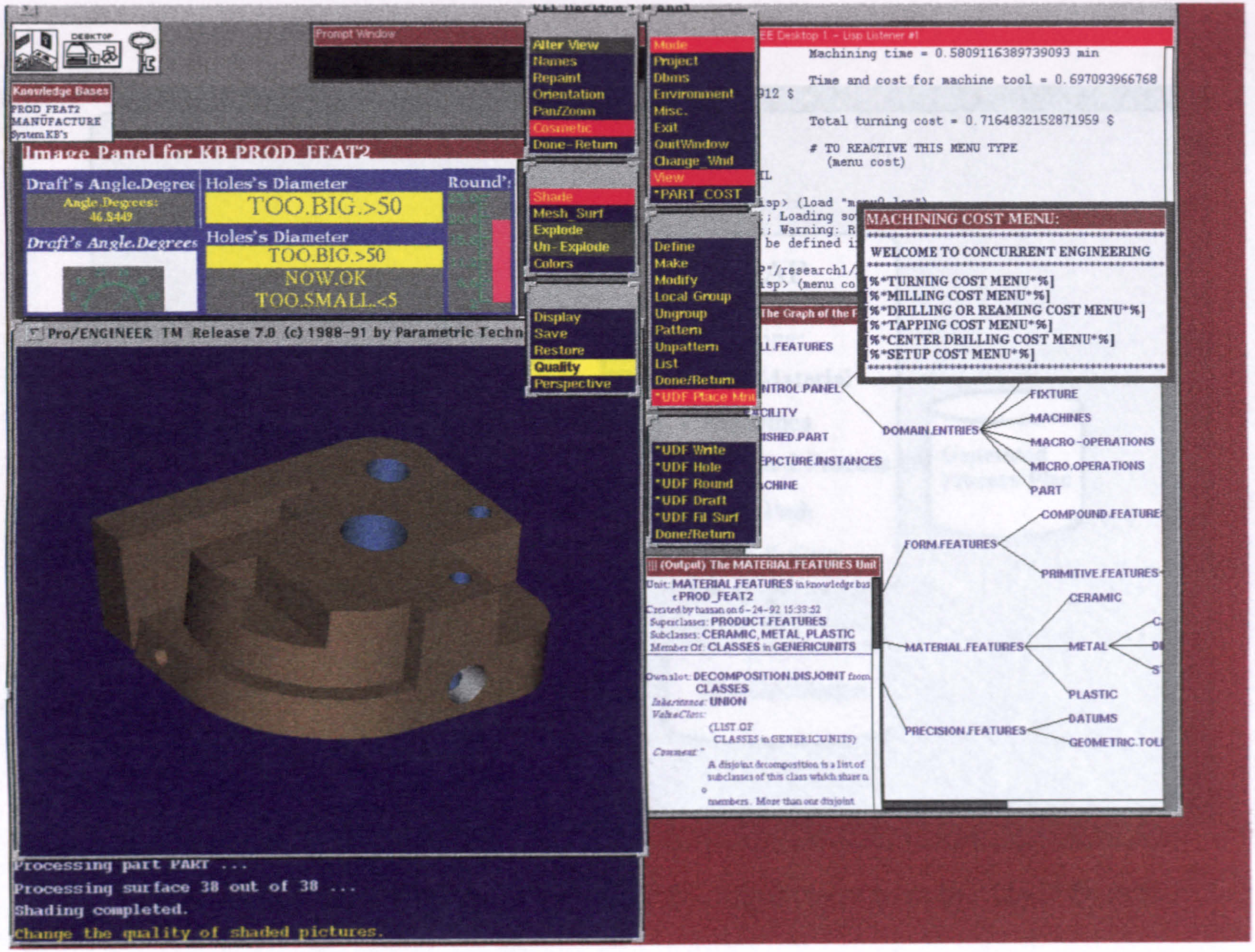


Figure (5.4)The Integrated System for Concurrent Product and Process Design

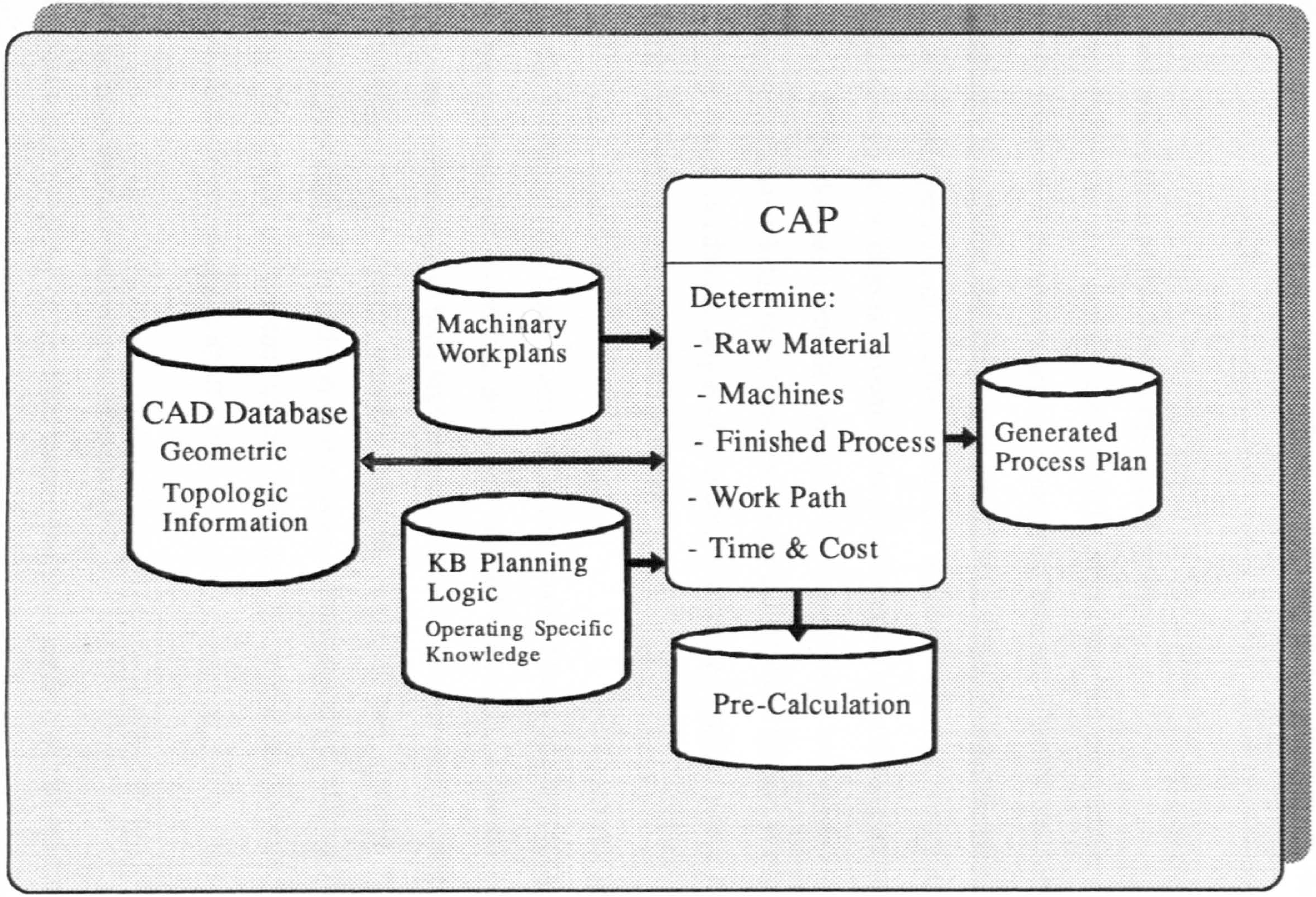


Figure (5.5) The Illustration of the PPS Interaction with the CAD Database manually. User interference here is necessary to complete all the design and manufacturing data needed for generating a complete process plan. Other information such as the type of material and machines available in house are structured in both the Database and the Knowledge-based Module of the PPS. All this information is interdependent and has been configured using rules and constraints which must be satisfied in order to generate a process plan.

5.4 The Construction of the Knowledge-based System

The knowledge-base was initially developed by identifying the prospective elements and objectives involved in the design and manufacturing process. The objects comprise classes and instances that define the features of the system. Each object has its own slots and methods for the operation of functional activities affiliated with that particular object. The classes give each of the objects its own distinctive properties while slots represent an object's behaviour. These slots and methods together with their attributes and values are furnished to each object in the knowledge-base. This then allows the Inference Engine to infer and extract any related values, conditions, sequencing order, or recommendations which are dependent upon the requested problem data from the user.

Generally, the knowledge base consists of diverse kinds of facts and heuristics, in order to store and manage the knowledge so it can be used effectively, a variety of knowledge representation schemes have been implemented and developed for that purpose. In principle, the Knowledge-Based System contains rules for analysing part features (topology and geometry), and material. In addition to extensive information about existing manufacturing facilities. The major components of the KBS and the interaction process between the different elements are shown in figure (5.6).

5.4.1 Product Feature Inheritance Hierarchy

The inheritance hierarchy of the KEE system has been used to model product features as shown in figure (5.7). There are two root classes the first one is the product features and the various *product.features* can be categorised as: *form. features*, *material.features* and *precision.features*. The second one is the facility features, and the various facility features can be categorised as: *cutting.tool.features*, *fixture.features*, and *machine.features*.

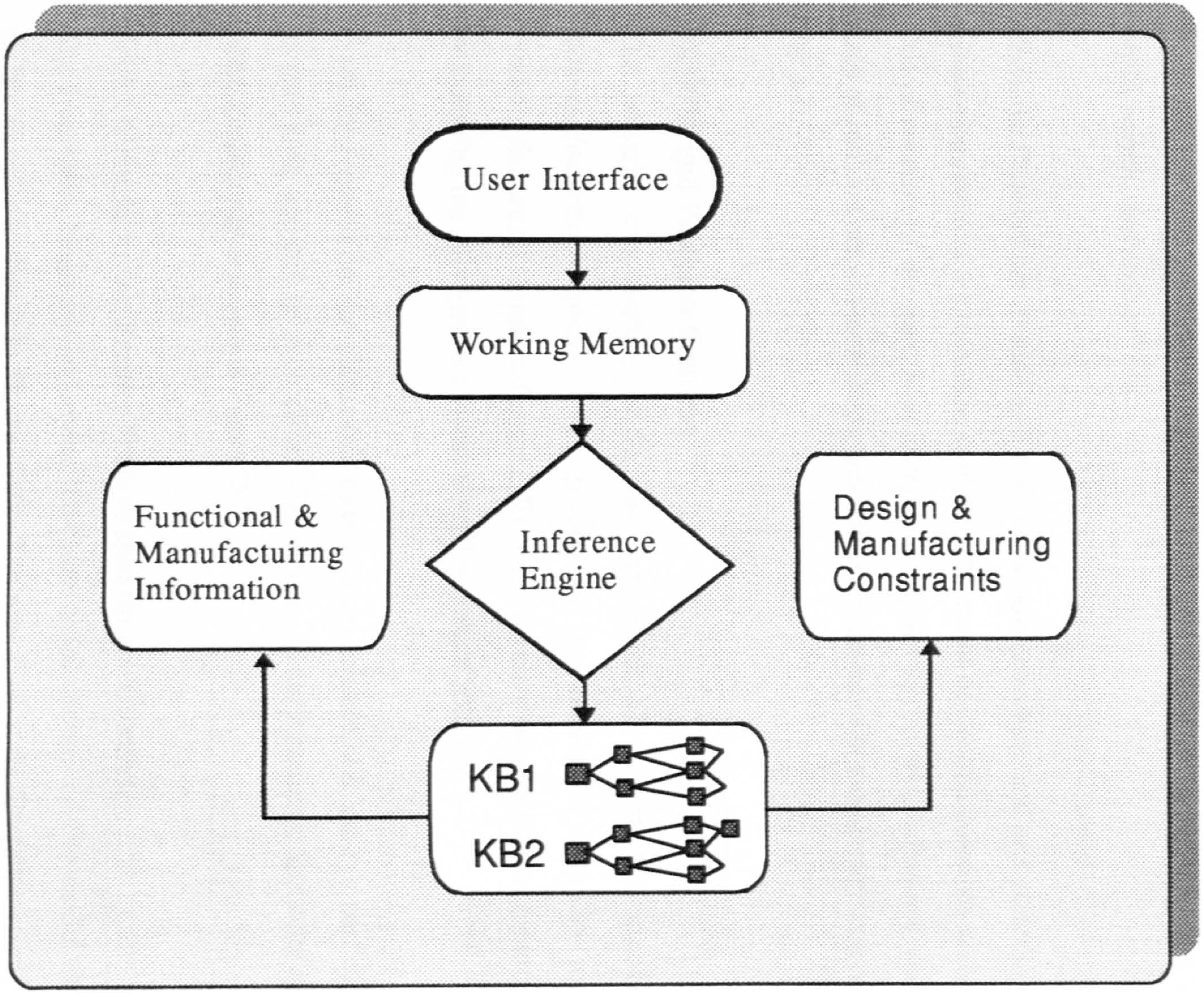


Figure (5.6) The Illustration of the KBS Components

5.4.1.1 Product Features

Form Features

Form.Features are presented as a subclass of the *product.features*; and can be classified broadly into two subclasses: *compound* and *primitive.features* (see figure 5.7). *Compound.features* are broadly divided into two units: *external* and *internal.features*. *External.feature* can be further classified into subclasses such as *draft, fillet, and round.* Each unit has a slot which contains various information about the unit characteristics such as *depth, length, and radius.*

Primitive.Features are divided into two subclasses: *concentric* and *non-concentric.features*. *Concentric.features* are rotational features whose axis of rotation coincides with the primary axis of rotation of the part. *Non-concentric.features* are rotational features whose primary axes of rotation are different from, and non-coincidental with the primary axis of rotation of the part.

Material and Precision Features

The material composition, grade, and properties of a part are specified by the *material.features* hierarchy. The portion of the inheritance hierarchy rooted under *Material.features* is shown in Figure (5.7). The material characteristics of a part are specified by indicating the appropriate material from this class of features.

Precision.features are the class of features used to indicate how much a part can vary from its true form and still be acceptable. The portion of the inheritance hierarchy rooted under *precision.features* is shown in Figure (5.7).

5.4.1.2 Manufacturing Facility Feature Inheritance Hierarchy.

The inheritance hierarchy underlying the frame-based system used to model manufacturing facility features is shown in Figure (5.7). The root class is *facility.features* and the various facility features can be categorised as: *machine.features, material.handling.features, fixture.features and cutting.tool.features.*

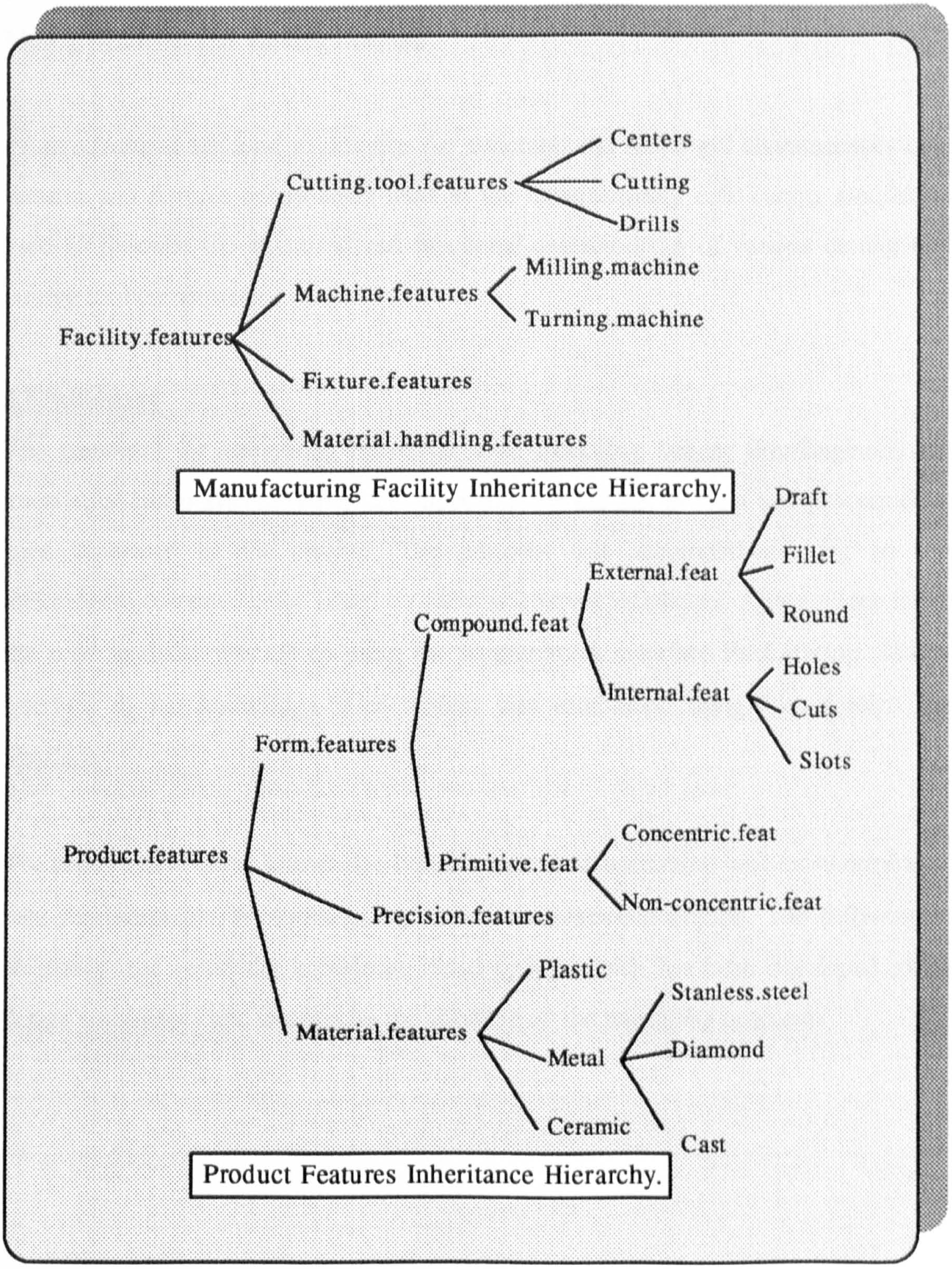


Figure (5.7) Features representation in hierarchy

Machine.features and material.handling.features are used to characterise the various machines and material handling equipment available in a facility. The attributes of machine features describe the various types of machines available in the manufacturing cell such as, Milling Machine, and Turning Machine.

Fixture.features are used to describe the structural and functional characteristics of various fixtures and fixtures components used in the manufacturing cell. *cutting.tool.features* are used to describe the structural and functional characteristics of various cutting tools and cutting tool components.

5.5 Summary

The paradigm for integrating the CAD solid modelling system (Pro/Engineer) with the knowledge-based system (KEE) for supporting concurrent product and process design has been illustrated in this chapter. The protocol was accomplished using an advanced interprocess communication based on client and server techniques. Above all the interface to the solid modeller was set up using the programmatic interface Pro/Develop. Similarly the interface to the knowledge-based system was established using Lisp foreign functions interface.

The construction of the knowledge-based system is demonstrated with more emphasis on the data representation in hierarchy, and inheritance between objects. The following chapter illustrates the constraint knowledge-based system which has been developed to maintain design consistency and to optimise the selection of the machining processes.

CHAPTER 6

THE KNOWLEDGE-BASED CONSTRAINT DESIGN SYSTEM

6.1 Introduction

Design inconsistency is a major problem facing designers, especially when they consider downstream and top-stream activities at the same time. One approach to this problem is the use of a knowledge-based constraint system that contains a wide variety of information about design, process, and manufacturing rules. Such a system should be able to provide advice to designers during the product life cycle development stage. Bowen and Bahler (1993) have investigated the possibility of a concurrent engineering oriented language based on the concept of constraint networks. These constraints have the capability of restricting the values that can be assumed by a group of one or more parameters. A knowledge based computer environment that supports Concurrent Engineering by integrating and providing active assistance for various engineering activities, such as conceptual design and redesign, specification acquisition, and qualitative simulation has been described by Tong and Gomory (1993).

In this research a more practical knowledge-based constraint system is developed to maintain design consistency and to support the selection of an appropriate machining process according to pre-defined constraints. The system has a database which maintains the consistency of a design constraints. A number of constraints about the existing manufacturing facilities and expertise are formulated using the knowledge-based system (KEE) rules. These constraints are implemented to identify the appropriate machining processes and to show the feasibility of a design during the design stage and before making the final prototype. A set of manufacturing criteria have also been included as rules to approve constraints. This combination of design and manufacturing constraints enables designers to examine whether the designed part can be manufactured with the available manufacturing facilities or not.

6.2 Classifications of Constraints by Domains

The system encompasses constraints from multiple functional resources, such as design, planning, production, and desired goals, which contributes remarkably in reducing the product development life-cycle. These constraints were classified according to the product life-cycle domains as shown in table (6.1). Further emphasis was directed towards two major types of data; the topological data which represents the shape of each feature and has been represented in terms of classes and subclasses. Geometric attributes entails information about each feature in terms of dimensions, surface finish, position, and tolerances. Manufacturing features are the outcome of applying the information of the design features, such as tolerance, and roughness to a design feature. For instance, to assign a manufacturing process (Laser, EDM, Drilling, Boring or Reaming) needed to originate a hole, both the design and manufacturing feature constraints have to be all true or satisfactory.

Domain	Constraints
Design	Dimensions,
	Geometric Relationships,
	Tolerances,
	Thermal Properties,
Process Planning	Material
	Manufacturing Facilities (Tools, Fixtures, etc)
	Operation Sequence
Production Schedule	Product Lead time
	Tools and Machines accessibility
Desired Goals	Cost
	Quality (Surface Finishing, Tolerance, ..)

Table (6.1) Classification of Constraints

The constraints structure is set up using Lisp functions along with the forward and backward chaining rules of the reasoning system KEE. The use of an object's inheritance was essential because constraints from different phases are inter-dependent, in a sense that constraints can be activated upon in the evaluation of another constraint. Constraints are also associated with artifacts and when the attributes of an artifact change, the constraints related to that particular artifact are activated. Further discussion concerning how the system tackles these various types of data in an interactive manner is explored in the subsequent sections.

6.3 Knowledge-based System Constraints

Designing by constraints technique has implications for the way designers use and specify tolerances. The raw material has its properties and dimensional distributions specified during the design stage, and thus has a tolerance band which is known to the computer and can be displayed to the user. All tolerances have to be identified and must be included as constraints. This information or knowledge centre of the system is of paramount importance in the operation of the complete system. It is the core of intelligence to the system when embedded with the operation sequence, design facts and data, design decisions and remedies, feedback messages, and other information that contributes and determines the capability of the system to satisfy the design specifications.

A set of design criteria and manufacturing rules are incorporated in the current system to monitor the design consistency and to determine machining operations, such as turning, drilling, milling, in addition to non-conventional techniques such as Electrochemical, and Laser machining operations. The structure of the knowledge-based constraints system developed in this research is illustrated in figure (6.1).

6.3.1 System Construction

The system consists of four major components or modules: design feature constraints, manufacturing feature constraints, process selection module, and a process plan system. The necessary information for each design feature is extracted from the feature-based design system, using the approach presented previously in chapter (4). The system then checks the extracted data and propagates the design feature constraints and sends the data to the manufacturing constraints module after ensuring that all the constraints are satisfied. A dialogue usually takes place between the user and the system during the design phase until all constraint requirements have been completed. Feedback from the output, of both the design and the manufacturing feature constraint is directed to the part design stage in the case of either constraint violation or inapplicability, as shown in figure (6.1). Further discussion of the design and manufacturing feature constraints is demonstrated below.

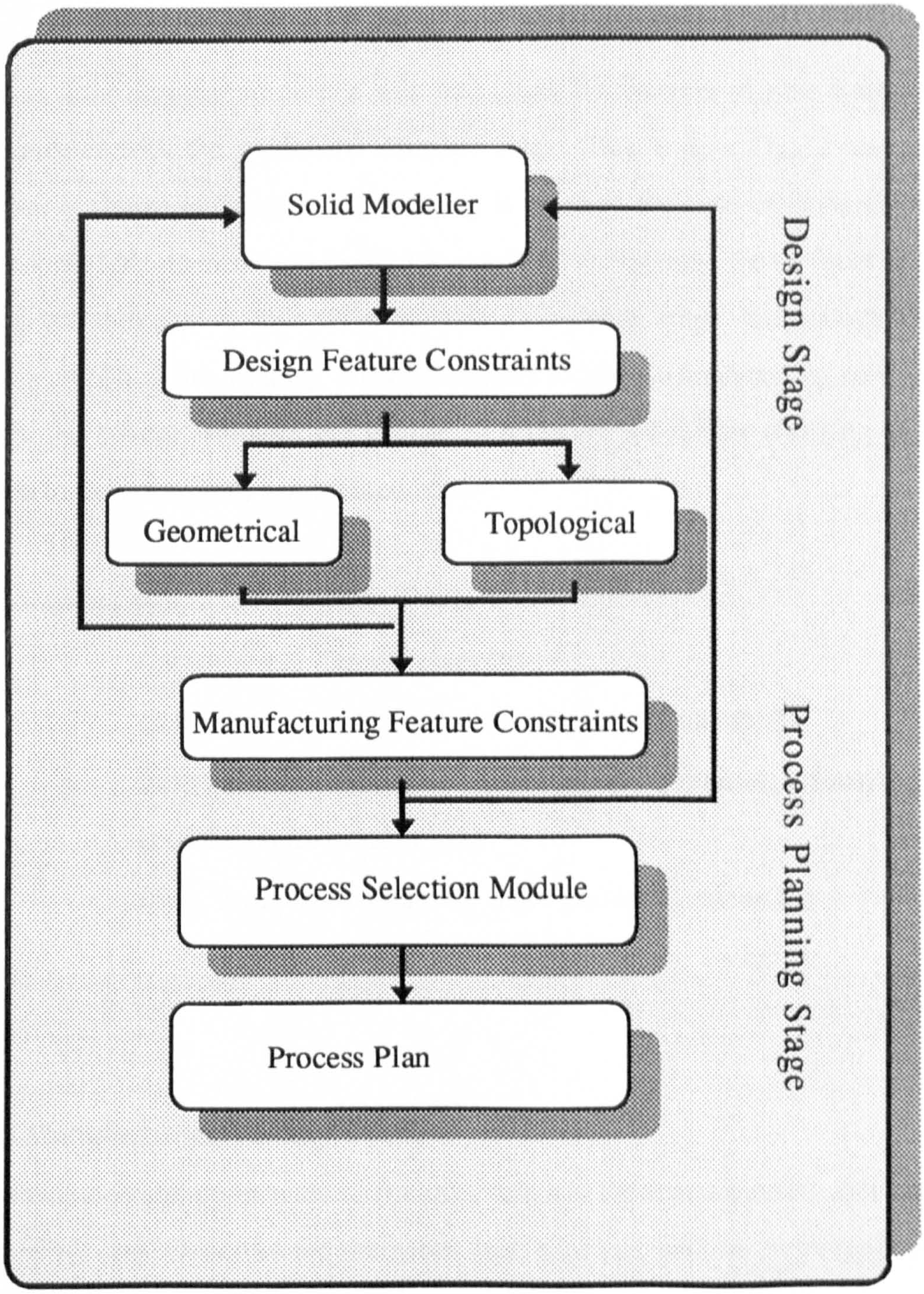


Figure (6.1) The Schematic Diagram for the Constraints KB System

6.3.2 Design Feature Constraints

Constraints are represented by mathematical equations and the geometric modeller is directly connected with the display objects. Therefore, when a designer changes a dimension of the object on the screen, the system automatically checks and evaluates these modifications. For instance, if the designer specifies a hole with a specific diameter (d_h) the system will compare this diameter with the predefined diameter range "$D_{min} < d_h < D_{max}$". An example of the program is shown in figure (6.2). Warning is given in the case of inconsistency or invalid dimensions (hole diameter too big or too small). Consequently, the designer can select other appropriate dimensions. This takes place at a very early stage during designing a product; implementation of this strategy allows designers to avoid manufacturing surprises. A sample of how the system estimates the volume of a feature for further checking of its validity in relation to the constraints is presented below:

```
(defun feature_volume (self)
        (let ((member_list nil)  (sum 0))
        (setq  ((member_list (unit.descendants self  'member))
        (cond  ((null member_list)  (unitmsg  self  'primitive_volume))
        (t (dolist  (unit member_list)
        (setq  sum (+sum  (unitmsg  unit  'primitive_volume))))
                                                    sum))))
```

6.3.3 Manufacturing Feature Constraints

The limitations and constraints of the materials and the manufacturing facilities, along with the quality, cost, customer requirements, lead time etc, have to be considered as early as possible during the product life-cycle development in order to meet today's market demands.

```
emacs: Emacs @ eng1
((unit holes in the prod_feat2 knowledge base)
  (created on
          "9-15-92 14:27:39"
          by
          "hassan"
          --
  (superclasses)
  (memberof internal.feat)
  (comment nil)
  (memberslots)
  (ownslots
    (depth (value (47.86))
           (inheritance nil)
           (valueclass (#[Interval: [10 60]]))
           (default nil)
           (activeimages3
            (#[Unit: viewport-depth-of-holes.32 prod_feat2]
             #[Unit: viewport-depth-of-holes.31 prod_feat2]
             #[Unit: viewport-depth-of-holes.30 prod_feat2]
             #[Unit: viewport-depth-of-holes.29 prod_feat2]
             #[Unit: viewport-depth-of-holes.28 prod_feat2])
            . unique.values)
           (cardinality.min (1))
           (cardinality.max (1)))
    (diameter (value (too.big.>50))
              (inheritance nil)
              (valueclass ((one.of too.big.>50
                                   now.ok
                                   too.small.<5)))
    (tolerance (value (0.251 < dim.tole <= 2.000))
              (inheritance nil)
              (valueclass ((one of drilling.< 0.500
                                   boring.< 1.000
                                   reaming.<2.000))))
              (default nil)
              (activeimages3
               (#[Unit: windowpane-diameter-of-holes.2 prod_feat2]
                #[Unit: windowpane-diameter-of-holes.1 prod_feat2]
                #[Unit: viewport-diameter-of-holes.27 prod_feat2]
                #[Unit: viewport-diameter-of-holes.24 prod_feat2]
                #[Unit: viewport-diameter-of-holes.23 prod_feat2]
                #[Unit: viewport-diameter-of-holes.22 prod_feat2]
                #[Unit: viewport-diameter-of-holes.21 prod_feat2]
                #[Unit: viewport-diameter-of-holes.20 prod_feat2]
                #[Unit: viewport-diameter-of-holes.19 prod_feat2]
                #[Unit: viewport-diameter-of-holes.18 prod_feat2])
               . unique.values)
              (cardinality.min (1))
              (cardinality.max (1)))))

--**-Emacs: kedit.lisp          (Lisp)----All------------------------------------
```

Figure (6.2) A sample of a constraint logic programming

An example for selecting the appropriate operation required to make a particular feature according to pre-defined rules or constraints is shown below:

If

(The Feature is a hole)	and
(The Diameter of the Hole $D_h >= 1$ mm)	and
(The Depth of the hole <= 200 mm)	and
(The Tolerance of the Hole < 0.01mm)	and
(Additional Rules)	

Then

(STEM Drilling is selected);

STEM (Shaped Tube Electrolytic Machining) is one of the electrochemical drilling techniques which have been accepted practice for a number of years for drilling fine holes.

6.3.4 Constraints Evaluation

The system is structured to evaluate the design and manufacturing feature constraints as long as the design process progresses. It operates by iteratively applying each constraint from the constraints modules to a part design and determines for each constraint whether it is satisfied, violated or irrelevant (inapplicable). Each constraint has a formula, the system substitutes the variables of each formula with given values and if the formula is true then the constraint is satisfied.

In the case of such a constraint violation, the system starts a colloquy with the designer regarding changes of one or some of a variable's values. When the designer modifies any of the variable values, then all the constraints will be automatically updated. The system also starts to propagate all the updated constraints, as this propagation is performed, each affected constraint is automatically re-evaluated since its status might vary due to the change which occurred to the variable values. This recursive procedure continues each time the user changes values or a constraint is been violated.

In some cases a constraint's status could be something other than satisfied or violated which is inapplicable. This type of constraint's status occurs when the user specify variables that have not been included in the constraints modules. An applicable constraint causes nothing special to occur until all the constraints have been processed and evaluated by the system. The system is designed in such a way to send instant advice to the user in the case of constraint violation. The user at this stage has two options either to accept the system advice or to proceed with his own decision. The system keeps checking all the constraints until they become completely satisfied.

6.3.5 Process Selection

This section illustrates the process selection for creating features using the developed technique. A good insight to the system is gained through demonstration of the necessary procedure for creating a feature by way of example. A good example to use is creation of a hole. Other features could equally as well have been used for the demonstration. Holes can be produced using conventional techniques, such as centre drilling, boring, and reaming as well as more advanced techniques, such as laser, STEM, etc. The selection of the process is based on a set of criteria including tool accessibility, cost, and tolerance which have previously been identified in the system. However, where design features require a fine surface, selecting a process becomes more complicated. For instance, a thru_all round hole would need center drilling, followed by a drilling operation and a number of finishing processes. Selection of a process depends also on the feature's attributes, such as diameter, depth, surface finish, and tolerance. The type of the feature has also to be considered, for instance a hole can be classified into different types as shown in figure (6.3), and the selection of the machining process are mainly based on its design feature type. Four groups of information are involved in the process selection:

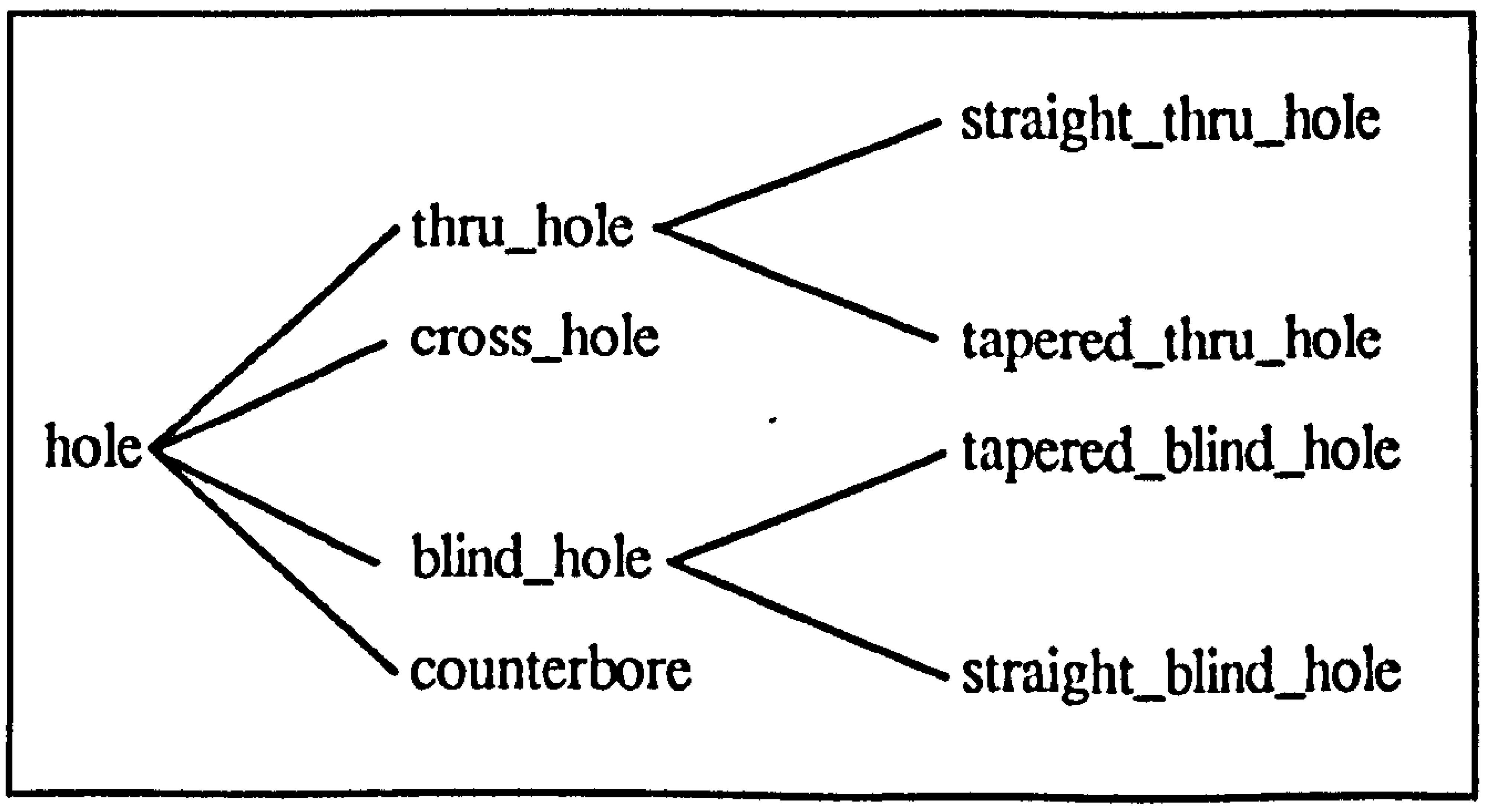


Figure (6.3) The hierarchy for different types of holes feature dimensions, tolerance, surface finish and cost. Dimensions in terms of feature's size, tolerance and surface finish apply to major surfaces of a feature. The manufacturing features are extracted from Bralla (1986) as shown table (6.2).

To select a manufacturing process that can be used to manufacture a hole, all constraints must be satisfied. For example:

if

(feature is a hole)

(type is a thru_all) and

(diameter < 15 mm) and

(0.001 <= diameter tolerance < 0.003) and

(accessibility is Yes) and

then

the hole is a reamed hole

Process	Surface Finish (μ in)	Dim Tolerance		
		0.251- 0.500	0.501- 1.000	1.000 - 2.000
Drilling	63-250	+0.006 -0.001	+0.008 -0.002	+0.010 -0.003
Boring	16-250	+0.001 -0.001	+0.001 -0.001	+0.002 -0.002
Reaming	32-125	+0.001 -0.001	+0.001 -0.001	+0.002 -0.002

Table (6.2) A Sample of Manufacturing Features

6.4 User Interface

The accomplishment of the overall user interface was structured and developed at different stages throughout the project duration. It encompasses a set of interactive elements which enable users to perform various processes such as input new data, update existing data, trace the design process, and retrieve data. These elements serve to form the front end link of the knowledge-based system. Design specifications or criteria stipulated by the user at this stage are down loaded to the working memory for further processing through functions made available to the user.

The interface is also structured to integrate the activities associated with the concept stage as well as the design process (figure 6.4), in addition to considering the correlation of objects, operations and its sequence.

6.5 Inference Engine

The inference engine is the system's controller or organiser which regulates the mechanisms involved in checking and satisfying a user's request. This theorem prover, upon being invoked by the user's input, would try to find values for variables within the constraints of the knowledge-based system that would make these constraints satisfactory. A constraint could be satisfied if its logic is true, a constraint could be violated if the logic is false, and a constraint could be inapplicable if the data does not match its rules or variables. When the constraint is violated, the violation detection system traces the possible sources of the violation and expose them to the users. At this stage the user has to modify the values of those variables in order to satisfy constraints.

The Inference Engine comprises a problem solving technique which is responsible for identifying the next piece of information to be used and scheduling other necessary activities. It is also responsible for ascertaining, when to ask the user a question and when to search for information. It ensures that all these operations are conducted in a concise logical manner and provides capabilities for dealing with inaccurate information. The development of the Inference Engine within the current research domain was engaged with a large amount of complexity including data acquisition and expertise.

The logic programming and support rules are written in an advanced common Lisp language. A set of rules were considered such as feature dimension rules, feature property rules, geometric reasoning rules, and operation rules.

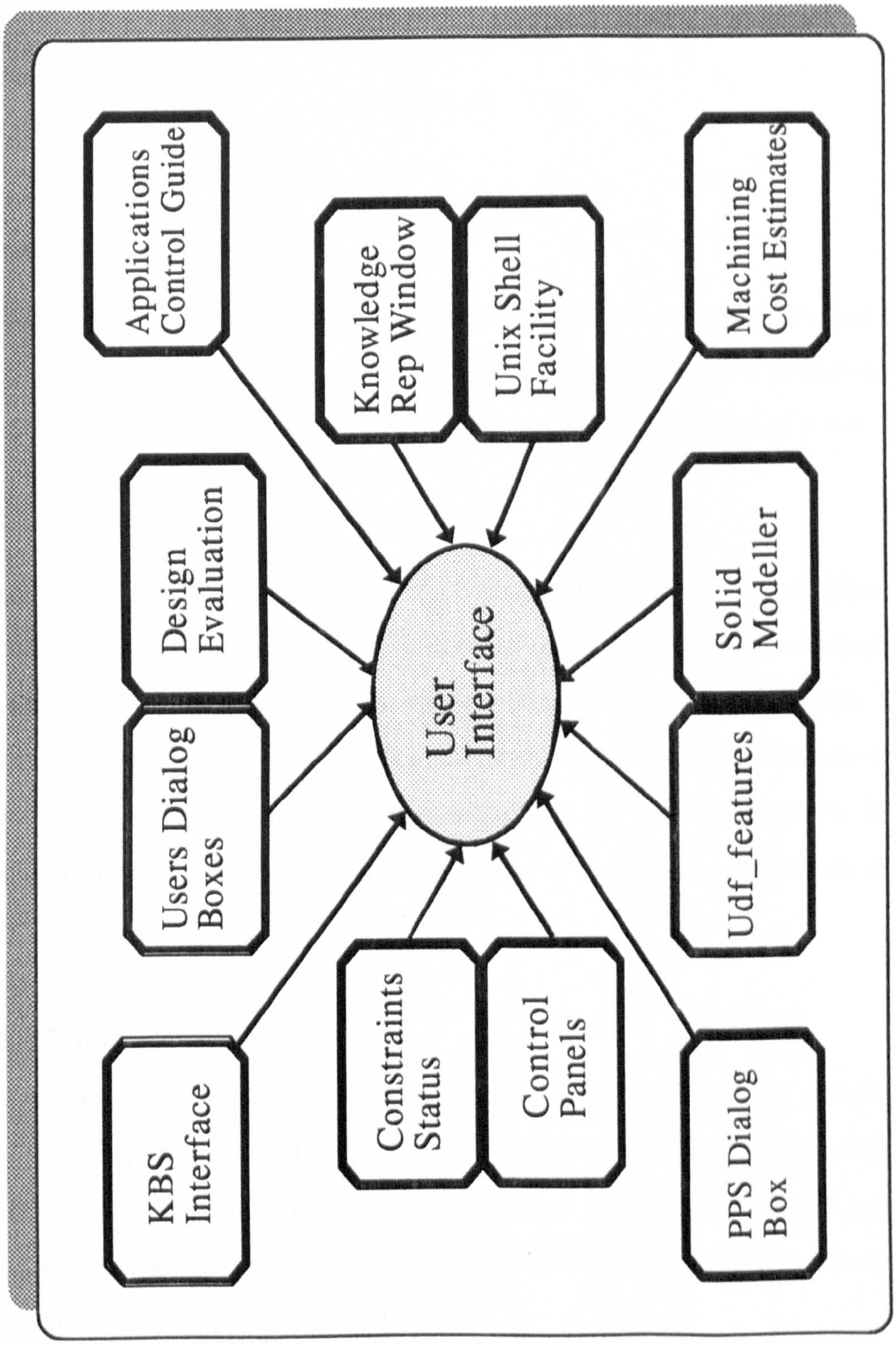


Figure (6.4) The Structure of the User Interface

The general syntax of the process selection and constraints validation are structured as follows:

Domain (variable, name, number)

If

(condition 1) and

(condition 2) and

(condition..n) True

Then

(conclusion or action)

The Inference Engine mechanism is based on forward and backward chaining that have been applied to the major rules, in the case of rule firing all the rules have to be examined and their conditions matched against the working memory. If the conditions of a rule are all satisfied then the operation is executed.

Usually, the functional requirements of a component commences with input of data from the user. This information may come in the form of constraints, specific problem data, production knowledge, or a combination of various facts. The Inference Engine then uses this information to infer the pre-defined intelligence of the knowledge-base and extract all the possibilities that would meet the pre-conditions in the working memory. If no solution is found, a message is displayed to inform the user of the invalid requirements stipulated by the user.

6.6 A Working Scenario

Introducing constraints from various functional sources, such as design specifications, manufacturing facilities, and targeted costs, as early as possible during the design stage, leads to significant reduction in the product development life-cycle, reduces the amount of rework needed, and improvement of the product quality. This also facilitates information exchange between different applications or experts.

Since there are interdependency between constraints from different domains or sources, the structure of these constraints is based on an inheritance approach. In this manner, constraints can be activated according to the behaviour or evaluation of another constraint. If the constraint is associated with an artifact it is archetypal activated when one or more attributes of that artifact changes. For example, a constraint on the tolerance of the diameter of a specific feature would be activated whenever the material or the tool is altered. This alliance was structured in slots, which contain parameters and objects that affect each constraint. When a constraint is violated, an instance of the constraint is created and an alternate solution or suggestion would be accumulated in the slot of that instance. If either a constraint or an artifact of that constraint still produces an error the system would keep sending a warning or a message indicating violation. At this stage the user would not be able to proceed with the design until all constraints have been satisfied. In some cases because of the complication of the interactive process of constraints from different domains, the system might generate other constraints that guarantee the satisfaction of others. The reasoning facility as well as forward and backward chaining of KEE was used to perform the constraints interaction during the design process.

A most significant benefit of this system is in the possibility to reduce product cost. After validation of the feature dimensions the system starts immediately to calculate the machining cost of each feature independently. The system then compares the estimated machining cost with the desired one and shows the results. At this stage the designer is able to interact with the system concerning features dimension modification for cost reduction.

6.7 Conclusion

This research has shown that a competitive and successful product design requires the implementation of a combination of sophisticated techniques and tools during the product development process. In order to improve design efficiency, a designer has to estimate the influence from-or-to engineering processes at early stage during the design session. In a real case, such interactions could come through design constraints or specifications. How to check and review the design process from the viewpoint of a series of constraints is very important in the implementation of an efficient CAD/CAM system. From these considerations, the system presented here was developed to have capability to show the design feasibility and constraint checking in the design process. The developed constraint Knowledge-based system shows the design consistency and assures that the design meets the desired goals. In this constraint model, constraints were used to represent relations between attributes of feature instances.

The system is effectively used to maintain consistency while generating feature instances and to propagate feature attribute values when adjacency relationship are established between feature instances. Information that must be shared includes the constraints that interact with and affect the solutions produced by each phase. At this stage the developed system provides a technique that evaluates and propagates constraints, and proposes solutions for violated constraints.

CHAPTER 7

SYSTEM IMPLEMENTATION AND APPLICATION

7.1 Introduction

The major goal of this chapter is to demonstrate how the developed system can be implemented to perform a number of functions during the design stage including creating features, extracting features, providing feedback a designer concerning design consistency, and estimating the machining cost of features. The following demonstration has been

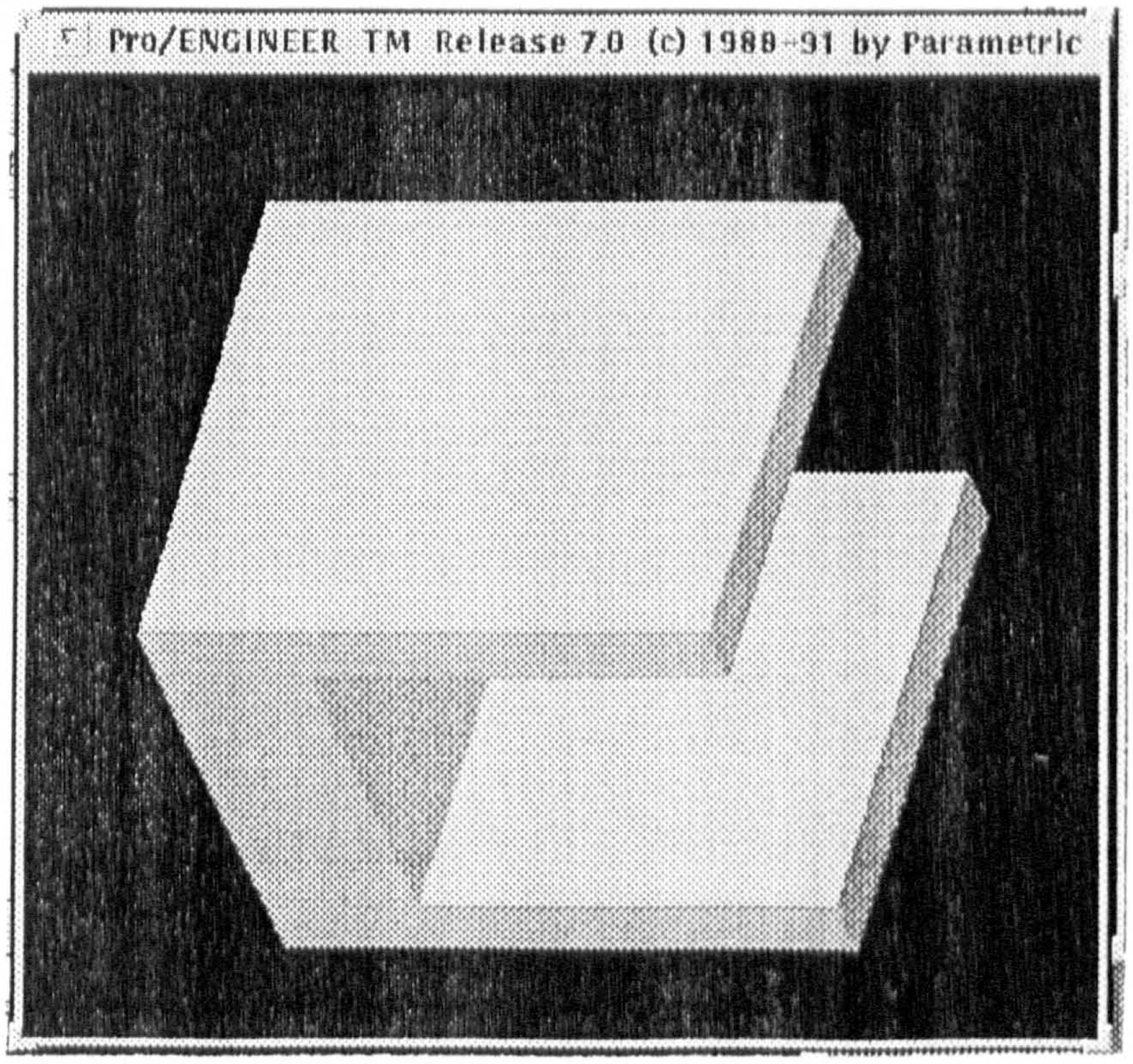


Figure (7.1) The Basic Shape of the Part

developed in a mechanical engineering domain, but it could equally as well be implemented in other domains. The scenario which the user has to follow to utilise the system is discussed in the following section. It has to be mentioned that this chapter congregates the techniques and procedures which have been presented in the previous chapters in more systematic manner for users to adopt.

7.2 The System Implementation within a Case Study

The workpiece used as an example in this demonstration is a U shape block with a set of form features on its surfaces. This type of component can be used in various applications, however the intent here is to pay attention to the features rather than the shape of the whole component. A number of features including holes, slots, rounds, and fillets are selected to show how the system works. The chosen component has a 100 mm width, 120 mm length, and 100 mm depth, two slots, five straight holes and is assumed that this part was made from aluminium. These are the initial dimensions of the basic shape, as shown in figure (7.1). This workpiece has to be machined to produce the finished part with a set of features as shown in figure (7.2).

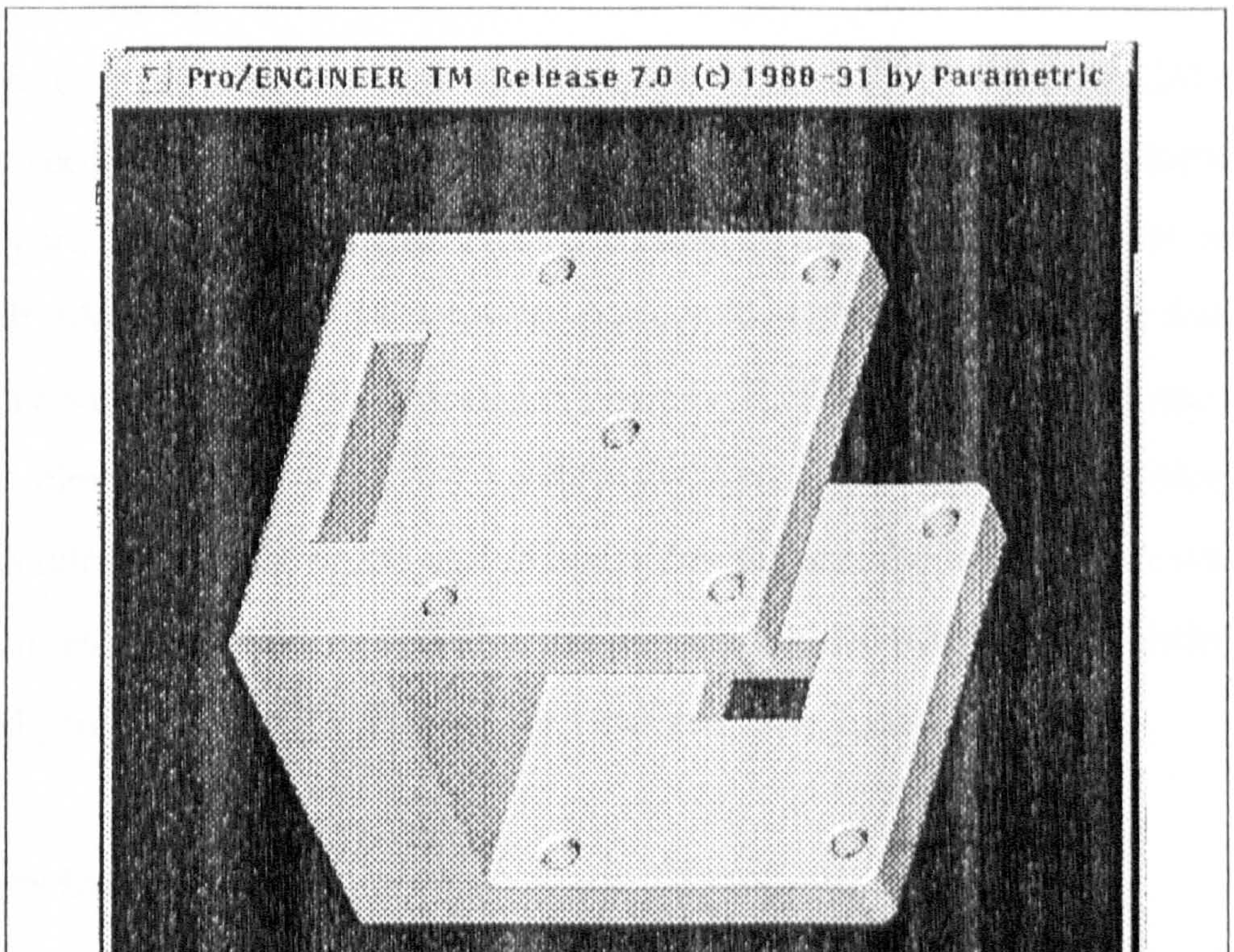


Figure (7.2) The Shape of the Finished Part and its Features

7.2.1 The Design Environment Interface

The user interface is split into five main regions, the region entitled **Image-Panel for KB Prod** indicates the current states of the design as it progresses. The region entitled **Manufacture-Knowledge Base** shows the feature created in hierarchy and gives further details about each feature represented in the tree. The region entitled **KEE Desktop-Lisp**

Listener enables the user to interact with the system regarding performing a number of functions, such as displaying the topological and geometrical information of the features and display them in the **Manufacture-Knowledge-Base** window, starting the machining cost estimation program, and performing a number of lisp functions. The region entitled **Machining-Cost Menu** is a pop up menu which appears only when it is necessary, in response to a user request. It incorporates a number of machining operation options that can be used for machining a feature. The final region is the **Pro/Engineer** CAD session which allows a user to build a model from scratch and use the enhanced menu icons to create features and send information transparently across to the KBS and vice versa.

7.2.2 Features Creation

First of all the user produces the basic shape shown in figure (7.1) using the CAD system facilities. The second interaction step within the design environment the features identified on the finished part, as shown in figure (7.2) are created. The designer uses the enhanced interface "Udf_Menu" to create the necessary features (five holes, two slots, five rounds and fillets on the two top surfaces) as illustrated in figure (7.2). The system creates these features with default dimensions. A user can modify the dimensions using "Icon_Modify" or "Icon_Regenerate" which allows the user to update/set the final dimension. After creating all identified features, the feature recogniser starts to create a database which includes all the topologic and geometric data for the part. As illustrated in the following sections.

7.2.3 Features Extraction

For recognising a feature, the system starts to find a set of faces and their attributes using the "User-defined Features approach" as discussed earlier in chapter (4). It then matches all the collected entities and their characteristics (types of edges, types of faces, etc.) with the predefined features for defining the feature topologically. The features holes, drafts, slots, and rounds have been defined as recognisable topologic and geometric patterns using a combination of the boundary representation scheme and constructive solid geometry. The feature recogniser extracts the feature attributes (depth, diameter, distances, etc.) and then sends it to the reasoning system for representation which can be used for various applications. At this stage the contrived database is accessible to any other program within or outside this application.

7.2.4 Features Representation in Hierarchy

The communication channel between the two components particularly the client invokes the proper lisp method which calls the connection to process all the extracted data. When the connection mode completes the process and receives all the data requested back from Pro/Engineer, it terminates the wait and check cycle and sends the data back to KEE through Lisp. KEE then acts on the received data and creates a corresponding data structure to store the information for further applications. The features are represented inside the knowledge-based system "Manufacture" as classes, each class represents an object. The classes give each of the objects its own distinctive properties, while slots comprise methods that represent an object's behaviour. Figure (7.3) illustrates the hierarchy of the features created within the Knowledge-based system "Manufacture" that has been created automatically by the system for that particular part.

7.2.5 The Constraint Knowledge-based System

Introducing constraints from various functional sources, such as design specifications, manufacturing facilities, and targeted costs, as early as possible during the design stage, leads to significant reduction in the product development life-cycle whilst reducing the amount of rework needed, and improving product quality. Since there is an interdependency between constraints from different domains or sources, the structure of these constraints is based on an inheritance approach. In this manner, the constraints are activated according to the behaviour or evaluation of another constraint. If the constraint is associated with an artifact it is activated when one or more attributes of that artifact changes.

In this application, the constraint on the tolerance of the diameter of a specific feature would be activated whenever the material or the tool is altered. This alliance was structured in slots, which contain parameters and objects that affect each constraint. When a constraint is violated, an instance of the constraint is created and an alternate solution or suggestion is accumulated in the slot of that instance. If either a constraint or an artifact of that constraint still produces an error the system keeps sending a warning or a message

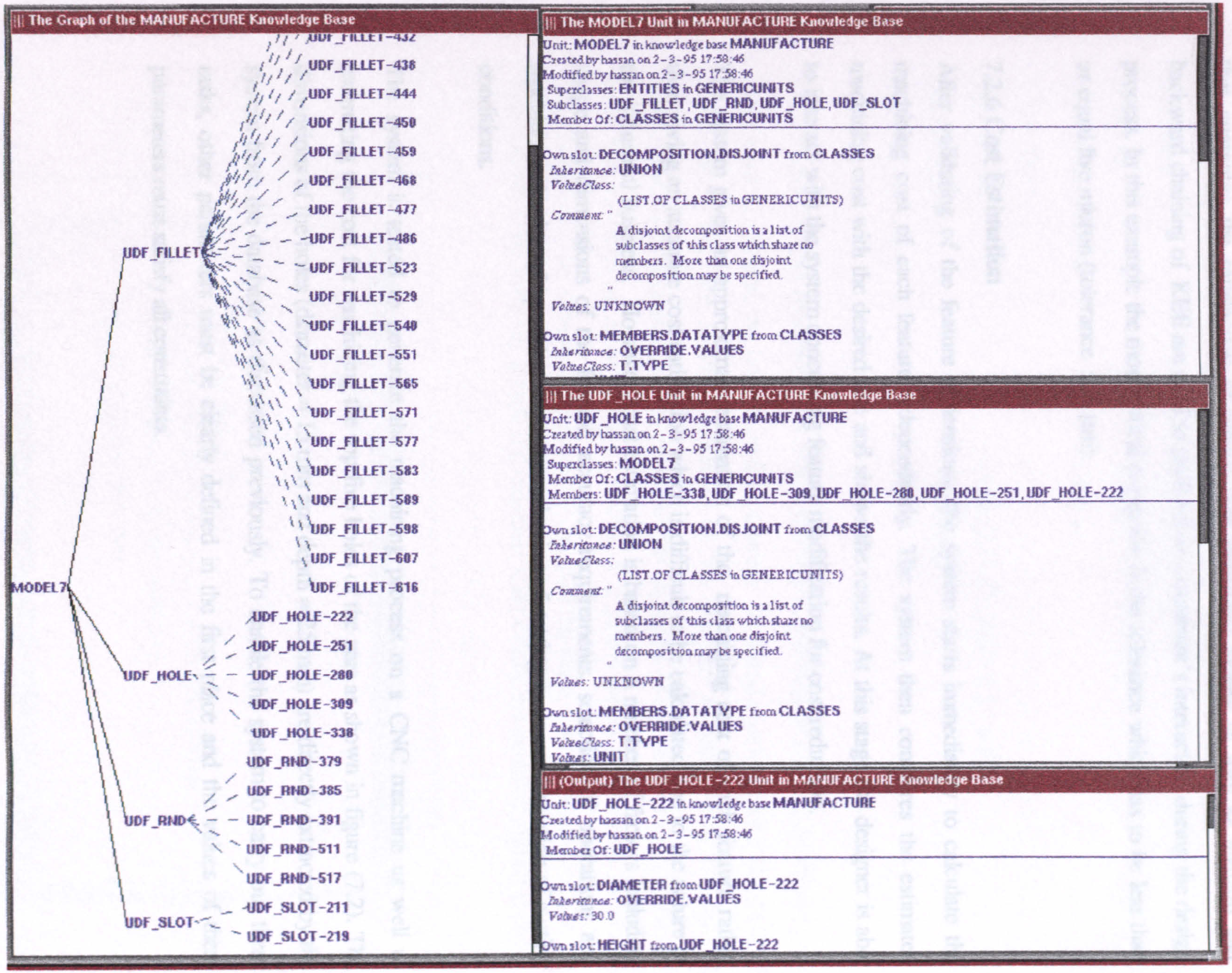


Figure (7.3)Features Representation in Hierarchy indicating violation. At this stage a user would not be able to proceed with the design until all constraints have been satisfied. In some cases because of the complication of the interactive process of constraints from different domains, the system might generate other constraints that guarantee the satisfaction of others. The reasoning facility as well as forward and backward chaining of KEE are used to perform the constraint's interaction during the design process. In this example the most critical constraint is the tolerance which has to be less than or equal five micron (tolerance ≤ 5 µm).

7.2.6 Cost Estimation

After validating of the feature dimensions, the system starts immediately to calculate the machining cost of each feature independently. The system then compares the estimated machining cost with the desired one and shows the results. At this stage the designer is able to interact with the system concerning feature modification for cost reduction.

The system gives an approximate estimation of the machining cost of each feature rather than giving an accurate cost estimation which is difficult to be calculated due to the nature of the industrial business. However, cost estimation is based on a number of factors including shape and dimensions of the feature, accuracy requirements, selection of operations and machines, selection of operation sequence, selection of cutting tools, and selection of cutting conditions.

The system is tested to generate the machining process on a CNC machine as well as estimating the cost for machining the top five holes of the part as shown in figure (7.2). The dimensions of the holes (diameter = 15 mm and depth = 25 mm) are directly extracted by the system from the database as discussed previously. To enable the system to carry out these tasks, other parameters must be clearly defined in the first place and the values of these parameters must satisfy all constraints.

The following assumptions are made to enable the system to perform the job:

Labour + Machine Cost/hr	=	£ 50
Batch Size	=	1.00
Material Type	=	Aluminium
Tolerance	≤	5 µm
Tool Life	=	90 min
Type of the process	=	Drilling
No of Passes	=	2
Type of tool	=	Delta Drill ∅ 29.00 (3.5 * d K20)
Spindle Speed	=	1415 RPM
Feed rate per tooth	=	0.35

To generate the five specified holes with a tolerance less than or equal 5µm requires two subsequent operations, the first is a drilling process for metal removal with Delta Drill ∅ 29.00 mm cutter. The specified tolerance on the diameter of the straight internal hole diameter features (tolerance ≤ 5µm) is beyond the capability of the chosen tool. Therefore to meet this tolerance an extra boring operation is required which leads to an increase in machining cost. The second operation has to be finishing using a boring operation. The next step after selecting the process type and sequence is estimating the optimum cutting speed

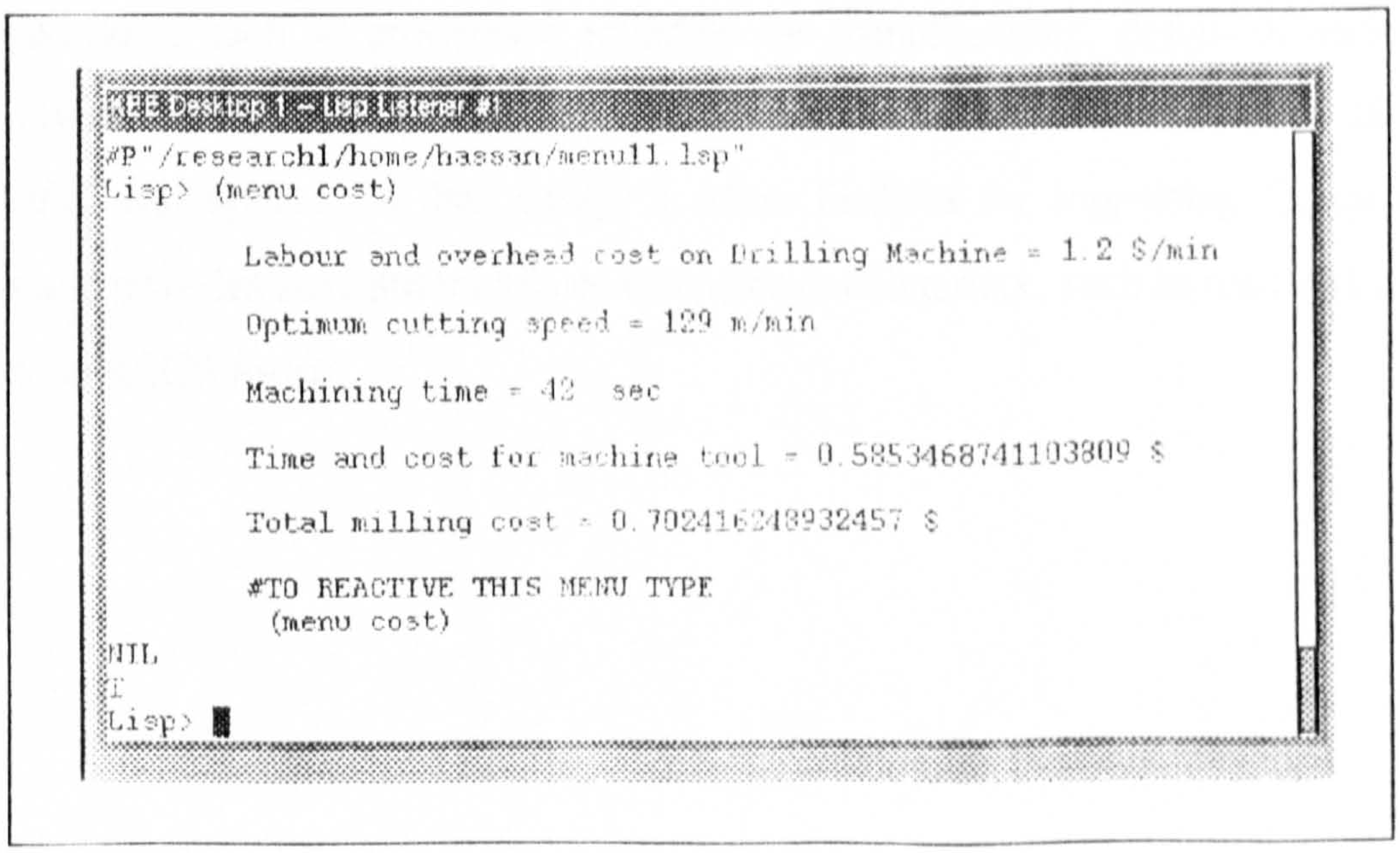


Figure (7.4) The Approximate Estimation of the Machining Cost based on a number of factors including type of material, tolerance, depth of cut, material of the cutter, feed rate, etc. The system substitutes all the above interrelated values in the program and estimates the optimum cutting speed for this particular operation, cutting speed = 129 m/min as shown in figure (7.4). The idea here is to give an approximate cost estimate for each feature individually, so users can distinguish the most costly feature from the cheapest one. Figure (7.5) shows the overall structure of the developed design environment.

In the case of cost exceeding the desired one, a designer can choose to consider changes to a feature's attributes and then to determine the effect of this change on the cost, as well as the final feature specifications.

7.3 Information Management Model

A Concurrent Engineering environment management system must have a clear strategy to co-ordinate and control the various types of complex data. An outline of the model that illustrates the information management throughout a product life-cycle development within an organisation is shown in figure (7.6).

7.3.1 A Standard Interface to the Process Selection System

The Process Planning System (ENGIN) was implemented to generate the process plan of each component. ENGIN is a rule-based CIM system, and can be utilised productively in various applications, such as production schedule for manufacturing, design of variants, calculation processes, and product configuration. It also has a batch system which allows users to change and update the data easily. It offers facilities for supporting Concurrent Engineering and provides standard interfaces to open a data interface, such as read and write external code in ASCII format.

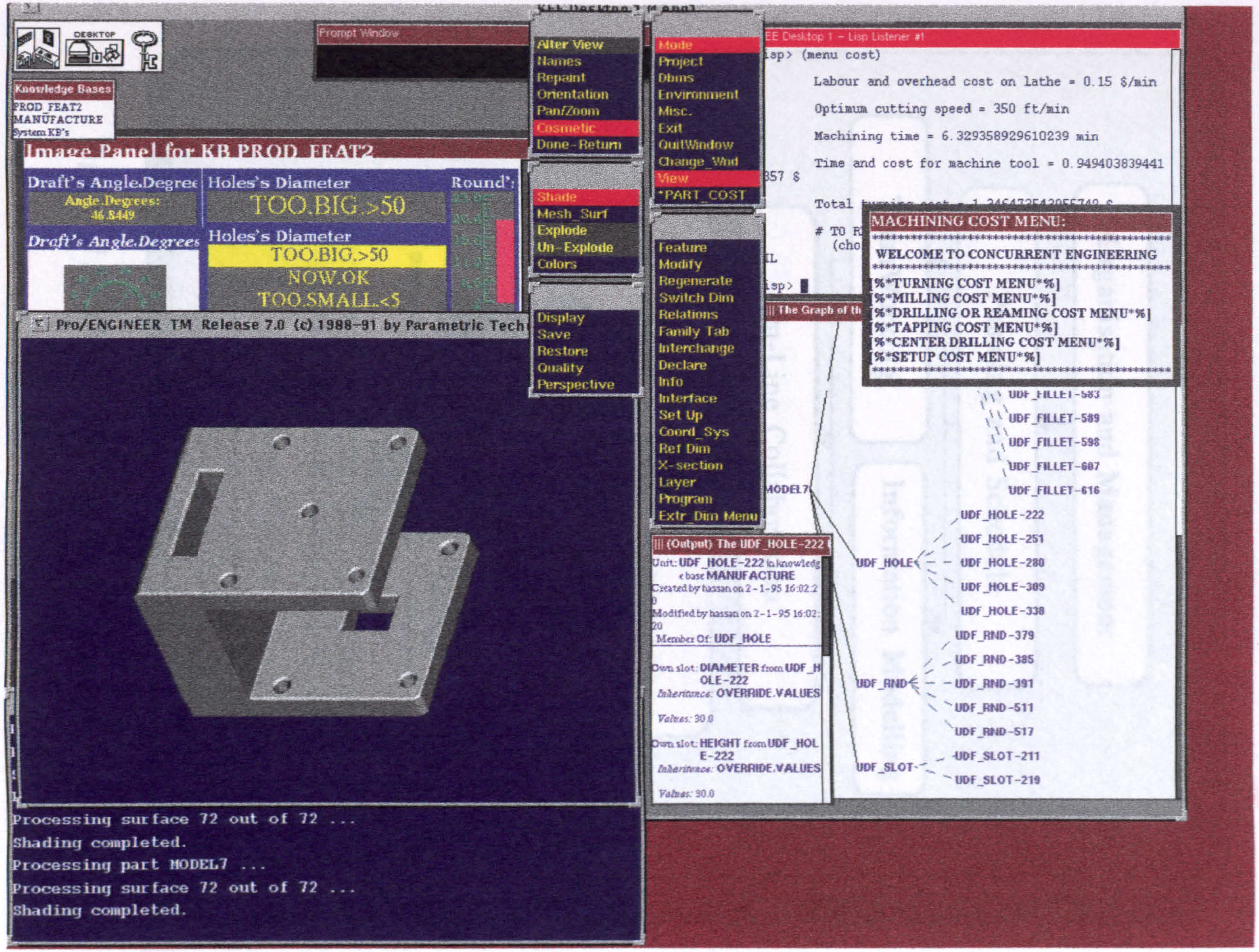


Figure (7.5)The Overall Structure of the Design Environment

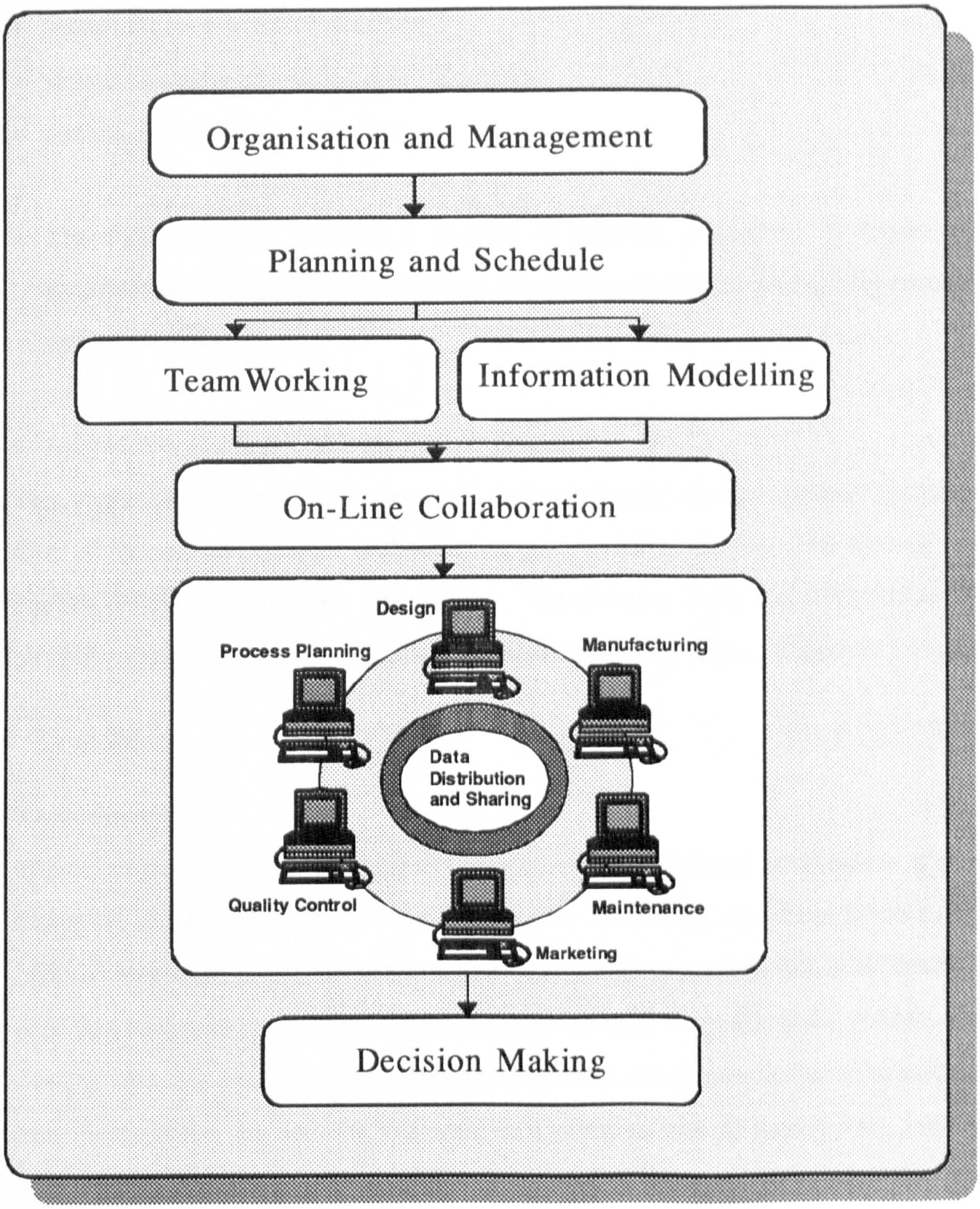


Figure (7.6) The Information Management Model

A number of applications can be carried out using SQL-interface, some of these applications are listed below:

- Interface to a CAD system database
- Access to material database for raw material selection
- Search for tools in a tools database
- Access to machine parts and cost information
- Access to a time-plan catalogues.

- The PPS (ENGIN) provides a number of planning possibilities in terms of tools specification, alternative operation plans, alternative operation plans, quality process plan, and process plan.

- *Information Formats within the Process Selection*

The expertise of specific domains were structured using the development system, in the form of decision-taking tables, arithmetic formulae, variables and files. This form of structure enables designers to optimise their design. The planning logic was constructed using a number of functions and a combination of decision-taking tables, arithmetic formulae and data files.

7.4 Summary

The developed system allows designers to interact with the design environment at all stages during the design session and not necessarily after completing the whole product design as happens with most of the systems available today. It gives an opportunity to ensure design feasibility and estimate the machining costs at a very early stage during the product life-cycle development. The system has been designed to enable users to obtain information about, not only the total cost but also the individual cost elements such as turning cost, milling cost, drilling or reaming cost, tapping cost, centre drilling cost and set-up cost. The system is utilising manufacturing knowledge in terms of rules, equations, and empirical data for estimating the process cost and manufacturability of a component. The most significant benefit of this system is in reducing product development time.

The infrastructure and requirements for controlling and managing the total product life-cycle development activities have been discussed in this chapter. The model basically illustrates the ingredient of a CE system and the role of each component encompasses in the model.

CHAPTER 8

DISCUSSION AND CONCLUSIONS

8.1 INTRODUCTION

This chapter summarises the major capabilities of the developed system and introduces some of the issues that have been drawn upon as a result of this research which require further investigation. A number of observations are discussed in section 8.2 of this chapter. The major contribution of this research to the area of design for manufacturability and concurrent engineering are outlined in section 8.3. Finally several important aspects for a future research work are introduced in section 8.4.

8.2 DISCUSSION

An Intelligent design environment for supporting concurrent product and process design has been developed within the framework of this research. This approach enables designers to consider manufacturing process design and product design to ensure the best matching of the final product specifications to ensure that a product will be manufactured with the existing manufacturing facility at high quality and lowest cost. The approach embodies certain underlying imperatives that help maintain communication between most components of a manufacturing system and permit flexibility to modify the design during each stage of a product's realisation. It provides facilities for designers to share engineering data including geometrical information, shapes, volumes and spatial relations. It also enables designers to modify, update or define geometrical information about design. In this context the object oriented programming and the rules of the reasoning system (KEE) are implemented to establish a technique for managing or controlling the sharing of various types of data and to keep design consistency.

The development of the system implied linking CAD/CAM software with a knowledge-based system toolkit. The problem of interfacing the CAD with the knowledge-based system was mainly due to the data incompatibility of the data generated in each application. Consequently, the CAD system had to be developed to provide information concerning design features for industrial applications (automation, design analysis, process planning, etc.) in a high level language.

The problem of extracting information in abstraction or high level language is tackled by developing a technique for solving the problem through implementing a dual scheme (CSG & B-Rep) for creating features, then establishing the interface to its database, as illustrated in chapter (4). The technique has been developed for that purpose using the facilities of the functions library of Pro/Develop accompanied by Codes written in 'C' language in a UNIX environment. The user interface has also been set up to enable users to interact with the system easily and effectively. Using this system the designer is able to create form features such as, holes, round, fillet, slots, and drafts. The system has the capability to identify features topologically and geometrically and extract the information needed from the CAD database instantaneously. The benefits of this are significant in a number of diverse applications such as process planning, and cost estimation, etc.

After solving the problem of information extraction the scenario for integrating the CAD solid modelling system (Pro/Engineer) with the knowledge-based system (KEE) for supporting concurrent product and process design is carried out. The protocol is accomplished using an advanced interprocess communication based on the client and server techniques. This integration between the solid modeller and the reasoning system is considered as an essential step for achieving the constructing this paradigm. A number of difficulties have to be overcome to establish this integration such as, KEE itself does not provide an external communication capability but allows complete access to Lucid's Common Lisp language. Common Lisp in turn supports a foreign language interface to communicate with PASCAL, FORTRAN, and C languages. These external languages are used to open, read, and write files as an alternative way of solving the problem. The second difficulty was that Pro/Engineer can only communicate to the outside world through the programmatic interface Pro/Develop which does not provide adequate facilities for solving the above problem, as discussed in Chapter (4).

The enhancement of the feature-based system and the integration of the various tools have contributed significantly in facilitating the product life-cycle development. It allows the product data and feature data to be transferred automatically from one tool to another avoiding the tedious traditional manual technique. This also enables users to share the same product data in various applications as mentioned previously, such as Design to Cost, Design for Manufacturability, and Design for assembly within a concurrent engineering environment.

The construction of the knowledge-based system which contains extensive information concerning product features and manufacturing facilities was a substantial element in completing this system. The construction of the knowledge-based system with more emphasis on the data representation in hierarchy, and inheritance between objects is performed and demonstrated in chapters (5 & 6). The system consists of four major components or modules: design feature constraints, manufacturing features constraints, process selection module, and a process plan system. The necessary information for each design feature is extracted from the feature-based design system, using the approach presented previously in chapter (4). The system then checks the extracted data and propagates the design feature constraints and sends the data to the manufacturing constraints module after ensuring that all the constraints are satisfactory. A dialogue usually takes place between the user and the system during the design phase until all constraint requirements have been completed. Feedback from the output of both the design and the manufacturing feature constraints is directed to the part design stage in the case of constraint violation.

The KBS is designed in a way to check and review the design process from the viewpoint of a series of design and manufacturing. Hence, the system has capability to show the design feasibility, design consistency and assures that the design meets the desired goals. In this constraint model, constraints are used to represent relations between attributes of feature instances.

The implementation of this knowledge-based system for Design for Manufacturability may be accomplished by sending the part description through the AFR technique to KEE after each design construction step to look for either machining cost or possible manufacturing problem areas in the part. A difficult to make feature such as a very small hole diameter, square corner pocket and so forth would be brought to the attention of the design as a matter of course for correction or, at least, for further contemplation.

The system is been effectively used to maintain consistency while generating feature instances and to propagate feature attribute values when adjacency relationship are established between feature instances. Information that must be shared includes the constraints that interact with and affect the solutions produced by each phase. At this stage the developed system provides the technique that evaluates and propagates constraints, and proposes solutions for violated constraints. Also, it is shown in the research that the design environment enables the product designer to minimise the machining cost of the product.

8.3 CONCLUSIONS

The progress achieved as a result of this research can be summarised briefly in the following points:

- The complete scheme for achieving the concept of concurrent engineering using IT tools has been demonstrated in chapter (3).

- The Solid Modeller (Pro/ENGINEER) has been enhanced by creating new Menus/Icons which enable designers to create form features such as holes, fillets, rounds, slots and drafts.

- A more efficient technique for an automated recognition of form features from a 3D Solid Model has been presented in chapter (4).

- The integration of the Solid Modeller and the Reasoning System (KEE) has been established using the interprocess communication described in Chapter 5, consequently the KBS can be interacted with the CAD package directly. The user is able to interrogate the KBS regarding performing the functions discussed earlier.

- The model for Constraints and Manufacturability evaluation that provides the designer with feedback during the design process concerning manufacturing implications of in progress design decisions, has been constructed, as presented in chapter (6).

- The developed knowledge-based system contains extensive knowledge (geometry and topology) about both the model features and the manufacturing facilities. It can be used as an intellectual information technology tool for achieving a set of goals; reducing time to market, improving product quality, and minimising material and production costs..

This system has been validated by implementing it for the concurrent product and process design of the specific models as presented in chapters (3, 5, and 7).

8.4 Future Work

This research work has emerged and contributed in providing the fundamentals needed for progressing the implementation of concurrent engineering strategy. However, more effort is required for establishing a more comprehensive paradigm for industrial practice. Extended work is currently being undertaken to include further technological information such as surface finish, heat transfer, and material requirement which are essential for the complete specification of manufacturing processes. A broad framework can be outlined for developing the current system to carry out the number of tasks needed for completing the paradigm. These tasks can be summarised as follows:

8.4.1 Short Term Plan

- Developing the feature recognition model to tackle more complex features.

- Further extensions to the form feature hierarchy to be carried out to distinguish between the type of primitive features that make up compound features.

- Completing the interface between the current system and an FEA package in order to allow designers to carry further mechanical analysis to the design during the design stage.

- Enhancement of the level of standardisation of the data and interface of the system to fully comply with a STEP and/or a CALS framework as discussed in Appendix (III). STEP and CALS are excellent models for facilitating data sharing and systems compatibility which are essential for practising CE. STEP contributes significantly in developing and creating new modelling and programming methodology. The identified requirement is to encourage vendors to comply with the standardisation of STEP and its framework. CALS covers some of the various methods and tools that can be used to support CE strategy. The major CE architecture mentioned were a "low road" system, a "high road" system, and a "middle road" with team approach.

- Gathering further real process planning knowledge from industry in order to have a realistic vision for the capability of the system.

8.4.2 Long Term Plan

- Product Life-cycle Phases Integration: the integration of all the product life-cycle phases leads to significant reduction of product cost, development time, product change, and increase customer satisfaction. This is due to the consideration of all the product requirements as early as possible during the design stage. This research is planned to investigate more thoroughly the methods, techniques, and tools needed to make that integration feasible. Topics such as cross functional teams, methods of communication, and efficient transfer of knowledge across the different phases may be investigated. The study may be focused on the soft aspects (human related) as well as the hard aspects (technology enabling). Developing a platform for facilitating the task would be considered. The integration is vital due to the variety and complexity of the product, and the rapid change in the global market structure in terms of insufficiency of technology compatibility, increasing demands on products characteristics and services and lack of flexibility of manufacturing facility.

- Global Management of all the Product Phases: the aim is to develop a platform that facilitates a global management of all the product-life cycle phases, from concept through to disposal and to centralise and distribute information amongst sectors. The platform is envisaged to encompass an integrated computer based tools, a global standard database system, a global computer network and methodologies that enable designers to keep design consistency and control the flow of information from different resources and phases. It also involves the automation of different functions and world wide distributed processes across different types of companies to produce a complex product. Global product management paradigm would provide an opportunity to shorten product development time, minimise engineering rework, decreasing product cost, improving quality, and delivering a product that meets customer expectations.

- A Concurrent Engineering Environment: a comprehensive study could provide information towards investigating technically how such a CE environment can be originated to suit various industrial sectors and individual companies. A detailed description of CE strategy could be applied to the various aspects of the product development process. Developing a platform on a computer system that could assist each company to simulate its product and search for details regarding how to apply different elements of CE to match their own product nature and complexity. It should also be flexible to reflect users, organisation or market change on the development process.

- Data sharing and communication technology: teams should be able to get access and share data throughout the organisation very easily, the preliminary step towards facilitating data sharing is data integration, centralisation, network system, and data standardisation. Cross-functional communication and simultaneous tasking between design, development, production and marketing departments to reduce overall product development time and to design product which more closely matched customer requirements. Information Technology (IT) tools such as engineering database management systems assist in getting information to the right people at the right time with minimum effort. The standardisation of different data models such as STEP is vital.

- This research could investigate an IT infrastructure that can support the flow of information between the people involved in all aspects of the business. Members of teams need effective and efficient ways of transferring data/drawings and also communication. The paradigm should have the capability to hold all information concerning a product and maintain the integrity of data.

- Communication Infrastructure: for improving efficiency and quality of internal as well as external communication of an enterprise to facilitate concurrency of tasks. Attention could be focused on establishing a platform that incorporates a set of facilities.

The research in this area is progressing, because the strong believe that these issues are worthy of further study, especially with the dynamic change of the market's requirements. The benefits gained during this research work are significant and useful in sustaining the dynamics of product development performance.

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Appendix I

Definitions

Form Feature: is a physical element of a part that can be identified by some generic shape and attributes. It has its significant in design manufacturing, etc.

Attribute: A characteristic, quality, or property of an entity. The entity could be a feature, a dimension, geometry or topological entity.

Feature hierarchy: An organisation of features into a family tree on the basis of common attributes, which are inherited through the links in a tree.

Geometric Model: A mathematical database that simulates a physical object, in terms of geometric and topological entities.

Feature Model: A database composed feature instances and their relationship.

Feature Validation: Determination of adherence to constraints, rules and properties contained in the normalisation of a feature. It implies a comparison of instance values to generic attributes.

APPENDIX II

Pro/ENGINEER Features

The following are some of the features offered in Pro/ENGINEER version 7.

- A mouse driven menu structure is used.
- A database management system is provided to manipulate the resulting modeller files.
- A running journal is kept and stored in an ASCII file. This can subsequently be reused with modifications if desired.
- Features can be added to a component in either part or assembly modes. This allows the inclusion of holes, shafts, chamfers, rounds, slots, protrusions and others.
- Features can be held in layers.
- The dimensions of all features can be shown to the user in two formats. One is the value of the dimension and the other is the modeller label for the feature.
- These features labels can be used to form relationships between features. Therefore the length of a box could be forced to be four times its height.
- Any feature can be suppressed in such a way that it is not shown on the screen or used in the integrity check, hence allowing a quicker and easier view of the model.
- Features can be grouped together and be used in a subsequent pattern within a component.
- Features can be copied and stored externally to the model for use at a later date.
- Datums can be created on the model for construction and referencing.
- Families of parts can be created thus simulating the type of operation that is used on 2D drawings where the drawing is used as a template for tabular data shown at the side of the drawing.
- Co-ordinate systems can be imposed on the model as a reference points used in the calculation of mass properties.

Appendix III

PRODUCT AND PROCESS DATA MANAGEMENT

The management of data as well as the integration of people, systems and information into one responsive are the most important and critical task for originating a Concurrent Engineering Environment. One of the approaches for facilitating this task is through computer systems, which allow automatic knowledge capture during the product life-cycle development, and automatic exchange of that knowledge among different computer systems. The major problem or the critical enabler is the way of handling the product data. An essential step towards promoting the data sharing of a complex product is through applying the engineering international Standards for the Exchange of Product Model data.

Full integration of industrial processes and standardisation of both hardware and software, especially standardised knowledge and knowledge models exist to allow inter-communication among all types of computerised systems are considered essential for supporting the process of making a competitive product. It enables people and companies to interact and perform their activities either individually or collectively, whatever style suits them. For example, within a manufacturing sector, computer aided design systems would be able to share information with analysis systems, manufacturing systems, and distribution systems. Standard systems will allow available information concerning a product to be accessible at every stage of its design, manufacture, support, and recovery or disposal.

The major requirements for a CE data management system, which allows designers to evolve the design process in a global enterprise perspective. A methodology for data sharing across multi-functional teams and the use of existing expertise in terms of knowledge, design and product processes, in addition to monitoring conflicts arising due to design inconsistencies are discussed in chapter (7). Such system should be able to capture, manage and implement continuously the evolved data, processes, and perhaps techniques.

- **Information Management Approach for CE**

Concurrent Engineering philosophy involves numerous experts from various background, disciplines, may be culture, objectives and attitudes to work together on designing or developing a product. This necessitates an overall co-ordination, control, standardisation, and integrity of design concepts, expertise or historical data, and goals in a well structured manner. An information system must have the capability to manage and control all the data coming from different resources and keeps it consistent. Research work has attempted to tackle these problems, most of this research work has been directed towards controlling, managing and modelling a product related activities in order to accomplish an integrated design and manufacturing process. The most recognised system in supporting the above concept is called PDES/STEP (1988) "Product Data Exchange Specification" which addresses the issues of managing a product related data.

- **A Standard for Product Data Exchange**

STEP and CALS are discussed as models for supporting an international standard for product data exchange. In addition to the progression that have been achieved within the framework of this research to support product data management and standardisation.

- **The Standard for the Exchange of Product Model Data (STEP)**

STEP is an international standard for product data exchange. It describes the product life-cycle in a standard format, which is suitable for sharing data across multi-disciplinary teams. It also provides a method for exchanging the physical and functional characteristics (data) of the life-cycle of a product in a complete way. These features facilitates the establishment of a common computer-interpretable system which includes information connected with design, manufacture, implementation, marketing, suppliers, and disposal to keep the data consistent, so it facilitates its exchange amongst various CIM systems. The different data sharing levels that STEP provides are:

1. the first level is physical file exchange- application protocols read and write data to files to exchange product data with other applications Knox (1993),

2. the second level is the programming interface called "Step Data Access Interface" SDAI which serves as a common software interface to product data applications,

3. the third level is the ability to provide the necessary description to Shared-Data-Base Implementations. This allows an application program to have access to the necessary data in a database through a neutral Step Data Access Interface.

- **The Structure of STEP**

The basic structure of STEP encompasses a number of components, each component has a unique function to perform within STEP format, ISO CD (1992). A brief explanation of each element is presented below as follows:

Description Methods:

These methods are used to define formal data specifications and graphical representations of a product using EXPRESS language. The description includes information concerning a product design methodology in terms of facts and concepts.

Integrated Resources:

The integrated resources comprise a number of product data descriptions called resource constructs. Each resource construct encompasses a set of EXPRESS language entities, rules, functions and references that are used to define valid descriptions of a product data.

An Application protocol (AP):

AP demonstrates the use of the integrated resources to satisfy the scope and requirements of a particular application. It also describes a product information model, conceptual model of an application.

Conformance Testing Methodology and Framework:

It is a part of STEP structure that provides the general technique for testing the conformance of a software product that would utilise STEP application protocol.

Abstract Test Suite (ATS):

ATS is been used to support the conformance requirements of a set of abstract test cases for an application protocol.

Implementation Method (IM):

The implementation methods include application programming interfaces, database implementations, and file exchange called "STEP neutral" that provides specific ways of using the application protocols defined in STEP.

There is no doubt that the advent of STEP supports and enhances the implementation of concurrent engineering strategy through data standardisation that leads to ease information exchange, communication, and systems compatibility.

- **Continuous Acquisition and Life-cycle Support (CALS)**

CALS is an American program aims to facilitate data sharing. The system deals with not only the information level but also with the functional level, and this makes the approach very appropriate as a tool for supporting CE. CALS strategy is to provide common languages for representing technical information allied with the life-cycle of weapon systems development. Consequently, enhancing the exchange of technical information between industry and the Department of Defence. Some of the topics which have been addressed within CALS framework are discussed below:

- *Automated Interchange of Technical Information (AITI)*

AITI is the core of CALS standard which provides the format and techniques for data exchange amongst different agents. It describes how complex information files can be organised and structured for storage on digital media such as magnetic tapes. There are also a number of formats for handling different types of information. For instance, MIL-STD-28000 Digital Representation for Communication of Product Data, which is mainly a standard for CAD drawings and vector graphics. MIL-R-28002A: Graphics Reproduction in Binary Format, which applies to scanned images, basically drawings.

- *Contractor Integrated Technical Information Service (CITIS)*

CITIS is the result of the second phase of the CALS standard development work. It allows a direct on-line access to contractor information rather than having these technical information on storage media. It also facilitates an access to technical information from various sources, Stickman (1993).

- *CALS Information Framework for CE*

This framework demonstrates the state-of-the-art of a generic CE information architecture, CALS Report 003 (1991). The main objective of this architecture is to enable "a large multi-disciplinary group to behave as a close-knit interdisciplinary team, creating, analysing, modifying and applying product data information in concurrent engineering".

- *CALS Handbook for Concurrent Engineering Practice*

The Handbook provides practical information and guidelines concerning the integration of design and manufacturing process, tools for supporting teamwork, and organisational issues for supporting concurrent engineering strategy, CALS (1992). It suggests two methods for improving communication between people working at various stages in the product life-cycle development. First, is a management technique such as collocation of team members, and second, is a corporate infrastructure which includes computer networks for information transfer and communication.

The Handbook has pointed out that there is lack of clear methodologies that could bring CE into practice. It has also addressed the substantial criteria needed for utilising CE philosophy:

- Multi-disciplinary teams that have representatives from all areas covering the product life-cycle.
- Standards for product information exchange.
- Global Management of the product life-cycle development and the practice of a Total Quality Management approach.

- Generic concurrent engineering services that support efficient and effective information and resources management.
- Computer based models of a product that could simulate design and manufacturing processes.

- **Total Product-life Cycle Management**

The section discusses a methodology for transferring technology and the co-ordination of a product development. Such methodology should determine the degree to which data from customers, suppliers, and all other business functions can be meaningfully organised and accessed by the development team members. This enables the team members to create a common understanding of a product and its related processes. The environment would also enable designers to carry on his design process with partial or incomplete information.

The major aspects that have remarkable influence on the total product-life cycle management within a concurrent engineering environment have been identified as follows:

♦ *Product and process classifications*: in terms of classifying or categorising "the product and process into independent or semi-independent entities". Product development process usually takes place on different stages including conceptual design, detailed design, design analysis, modelling, process planning, etc. According to the CE strategy all these functions should drive simultaneously to assure a high degree of collaboration and co-operative effort amongst the team. To carry out these functions or processes in parallel necessitates, good communication amongst the various departments, and clear management strategy. Most of the systems or tools available today support only individual process. Systems that have the capability to manage and control the work flow still lacking, Parasad et al (1993). Therefore, the need for developing such system that supports the parallization of the product and process design is crucial. However, the characteristics of such a system or tool for design aids have been identified:-

i) concurrent design process interdependence: this means that the tools implemented should enable designers to perform a function at one stage which is directly related to other functions at different stages independently without changing the characteristics of the final product,

ii) product parameters and function interdependence between the various functions: managing and co-ordinating the interdependence of multiple-functions is a critical task. This is because each product or company may require different approach to facilitate its functions interdependency. In addition to the rapid change in the market's requirements which increase the pressure on companies to evolve their product development concepts, and methodologies fastly and efficiently,

iii) product design consistency: CE environment is based on cross-functional teams as it is mentioned previously, this implies that those teams with different experience should be able to work together efficiently. The interdependency at this stage sometimes generate design inconsistency, design conflict, or multiple design alternatives. Therefore, the need for providing a robust and clear strategy for resolving design inconsistency, and conflicts is a matter of importance. Such CE environment must be flexible enough to co-ordinate and manage the performance of the parallel processes or activities without conflict or inconsistency. A feedback loop from one stage to another and from a function to another at the same stage must be considered to satisfy design conflicts and ensure design completeness.

♦ *Life-cycle interactions*: the interaction between downstream activities and upstream activities usually cause design conflicts or inconsistencies. Design, manufacturing, simulation, process planning experts have to collaborate to avoid any surprises. There are a number of information systems, feature-based tools, simulation systems that can be used to moderately facilitate the concurrency of these activities. In general, any CE environment must accommodate the development of an integrated information and the capture of data that includes both upstream and downstream information.

♦ *Knowledge propagation (KP)*: KP is the process of checking the validity of data related to a product and implemented processes. Phal and Beitz (1989) have classified the design processes into four major categories as follows:

1. fixed principle design, which has its potential for automation, since it contains established design information in the form of parameters and features;
2. adaptive design which helps to solidify the generality of the design and close the gap between fixed and original principle,
3. original design, is been used for knowledge capture; and
4. variant design to achieve efficient knowledge propagation, it is vital to have tools to support the above design processes.

PUBLICATIONS

An expert system for concurrent product and process design of mechanical parts

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A new approach for concurrent product and process design of mechanical parts is presented in this paper. This approach enables designers to ensure that the product will be manufactured with the existing manufacturing facility at high quality and lowest cost. It is composed of an integrated expert and CAD (computer aided design) system that meets the requirements for accomplishing the concept of design for manufacturability or concurrent engineering. The system is based mainly on three tasks: firstly, developing a technique for automated feature recognition from the database of a solid modeller; secondly, interfacing the expert system tool-kit with the solid modelling system; finally, building an expert system that contains extensive information about both manufacturing facilities and product features. The expert system provides feedback about manufacturing concerns such as process limits or design inconsistencies. This work is part of the present extended research plan for developing a generic system suitable for various manufacturing practices based on design for manufacturability strategy.

1 INTRODUCTION

Design for manufacturability (DFM) or concurrent engineering (CE) necessitates that product and process designs be developed simultaneously rather than sequentially. That means that all of the design constraints, including assembly, material information processes and material handling requirements, are included as part of the functional optimization of the design. In this way, the DFM process enables designers or a design team to consider all aspects of the product design and manufacturing at early stages of the design cycle, so that design iteration and accompanying engineering changes can be made easily and effectively. This has great advantages because it leads to few or no manufacturing problems.

A concurrent engineering approach has been illustrated in this paper, as shown in Fig. 1. It shows that CE strategy requires a parallel interactive team approach—a 'tiger team'. However, the full realization of such a co-operative team approach in product development practice is a very difficult task for the following reasons: firstly, lack of a comprehensive model clearly describing the decision activities in simultaneous product and process design; secondly, lack of sufficient computer-based tools, capable of supporting co-operative decision-making activities. Rehg *et al.* (1) presented a new system for computer aided mechanical design known as 'CASE', which stands for computer aided simultaneous engineering. Their system supports mechanical design at the project level, and serves as a means of integrating into the design process concerns from other parts of the life cycle of a product. Glover *et al.* (2) described the importance of 'synthesis' software tools to integrate reliability and maintainability into the early computer aided design environment, thus enabling productive concurrent engineering. A model for integrating multiple sources of knowledge within engineering expert systems is presented by Mayer and Lu (3). Their model allows possible conflicts between multiple knowledge sources to be logically resolved at run time rather than during the knowledge acquisition stage. Generally, CE aims at considering all elements of the product life-cycle from conception through disposal, including quality, cost, schedule and user requirements. The benefits of implementing the concept of concurrent product and process design are enormous, such as reduction of cost, improvement of quality, elimination

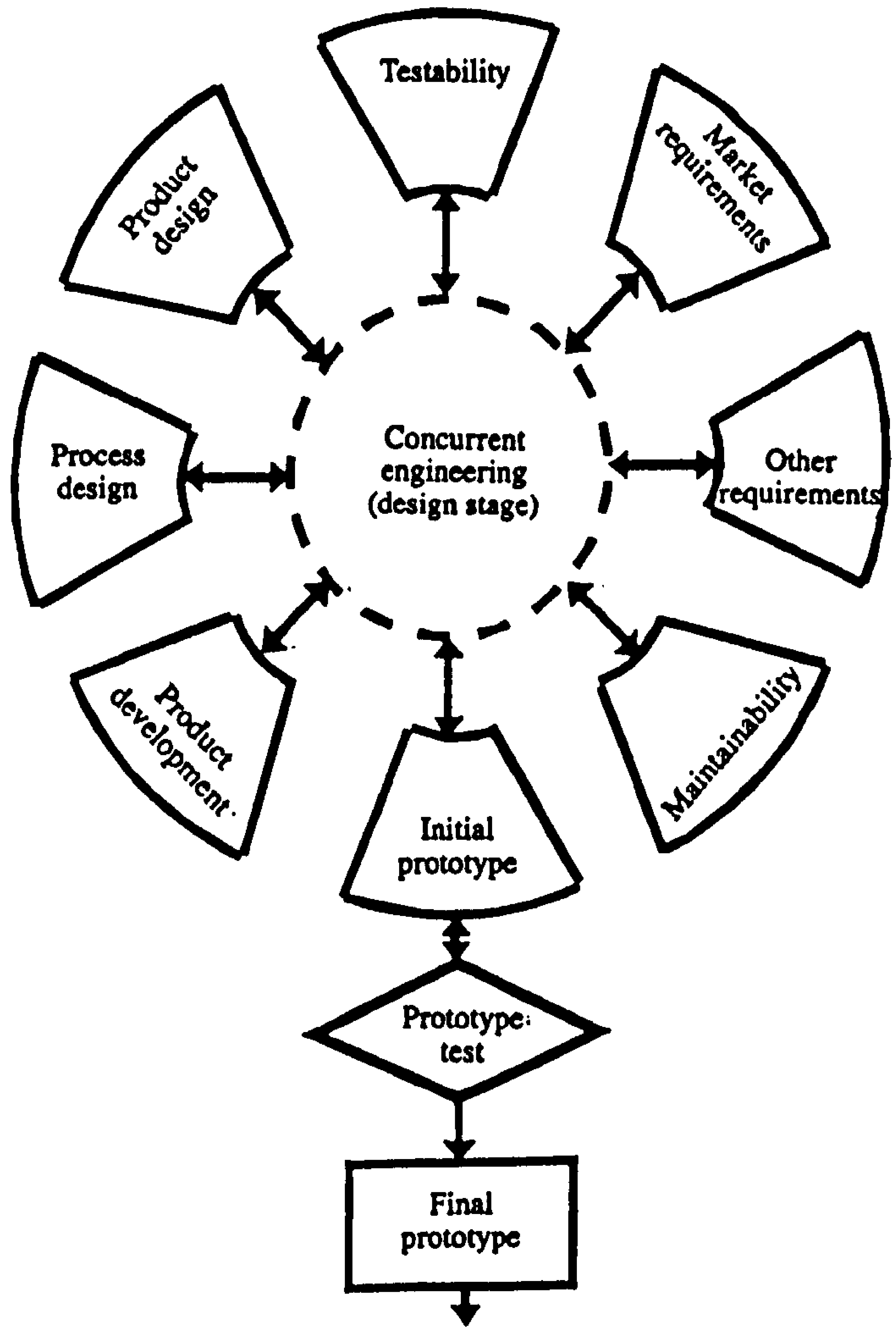

Fig. 1 An approach for concurrent engineering

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of waste, reduction in lead time for product delivery and continuous product improvement (4–6).

The role of features in design, in approaches for design for manufacture, in process planning and in cost information tools for designers is discussed by Wierda (7). His discussion revealed that feature-based models offer considerable advantages and have the potential to close the gap between design on the one side and process planning and cost information on the other. Miles (8) introduced the role and value of design for manufacture tools and techniques in a team-based simultaneous engineering design process. He also described a design technique for assembly (Lucas) and the benefits of its use in terms of parts cost reduction, assembly cost reduction and product cost reduction. Alder and Ishii (9) presented a framework for evaluating designs and providing suggestions called 'design compatibility analysis' (DCA), which incorporates both qualitative and quantitative data (that is cost estimates) to produce an overall rating for a design based on functional specifications and target costs.

CE and DFM philosophies are the key to minimizing life-cycle cost and design time, assuring product quality and increasing productivity. For instance, design for manufacture aims at identifying product concepts that are inherently easy to manufacture and assemble and integrating manufacturing process design and product design to make sure that the product meets the market needs and requirements. There are a number of DFM tools and techniques that can be implemented to produce significant improvements in product quality, life-cycle, cost, etc. These tools, such as CAD/CAM (computer aided design/manufacture), expert systems, DFA (design for assembly), CAPP (computer aided process planning), FMEA (failure mode and effects analysis), GTDB (group technology database), etc., can be used effectively and efficiently during the design process. This will enable designers to consider all aspects of the product's design and manufacture during the design session. For example, GTDB can be used for estimating cost of new parts based on the known cost of existing components.

A considerable number of studies emphasized the utilization of design for manufacture, but most of them have not addressed an efficient methodology to help designers conduct the discipline. Subramanyam and Lu (10) presented a methodology for the simultaneous product and process design of components manufactured in small and medium lot sizes. A key aspect of this methodology is to ensure that such components are manufacturable for the lowest possible cost in specially designed manufacturing facilities such as manufacturing cells. Abdalla and Knight (11) developed a knowledge-based system for cost effective design based on a solid modeller. Their system has been seen as an excellent step towards accomplishing the concept of concurrent engineering. However, the implementation of CE strategy has been shown to be a non-trivial task that needs to be overcome before the full benefits can be accomplished. This paper introduces an integrated expert and CAD system that can be used for achieving some of the CE goals. The paper is organized as follows: firstly, presenting an approach for automated-feature recognition from a solid modeller; secondly, linking the solid modelling system with an expert system shell tool-kit; thirdly, constructing the proposed expert system; finally, conclusions and recommendations for future work.

2 FEATURE-BASED MODELLING SYSTEM

2.1 Form feature definitions

A feature is an entity or geometric form. Its attributes (dimensions, shape, etc.) are very important for various industrial functions, such as analysis, evaluation, process planning, etc. The feature attributes must be represented explicitly in terms of forms that match available manufacturing knowledge. Form features such as holes, slots, cuts, rounds, notches, etc., have been given various definitions according to their intended usage. For example, Wierda (7) gave a very general definition for a feature; he defined it as 'a partial form or a product characteristic that is considered as a unit and that has a semantic meaning' in various engineering schemes such as process selection, manufacture, machining cost estimation, product and process design, etc. Chung *et al.*(12) have defined features as objects which may contain methods for geometry abstraction, geometric constraints, methods for geometry creation and modification, methods for manufacturing, analysis, assembly, inherited properties, etc. They proposed a prototype system which provides designers with a set of standard primitive features such as blocks, cylinders, pyramids, full/partial torus, cones/truncated cones, full/partial tubes and straight/circular fillets. These primitives are represented as an object class in an object-oriented programming methodology. These classes 'contain attributes which describe the characteristics and behaviours of its members'. Other authors defined features in two ways; the first is called boundary representation while features can be defined in terms of a set of edges, faces and vertices; the second is called constructive solid geometry and is specified as a set of primitive volumes, cylinders, cones, blocks, spheres, pyramids, etc. (13, 14). Figure 2 shows an example for a part and its form features. This part illustrates simple features only; complex features have not been discussed in this paper.

2.2 Feature recognition from a solid modeller

Current CAD systems represent drawings in two dimensions, wire frame models, surface models, solid boundary representation or solid constructive geometry models. This implies that the part or product is represented by sets of points, lines, surfaces and/or primitive volumes. This type of representation is not

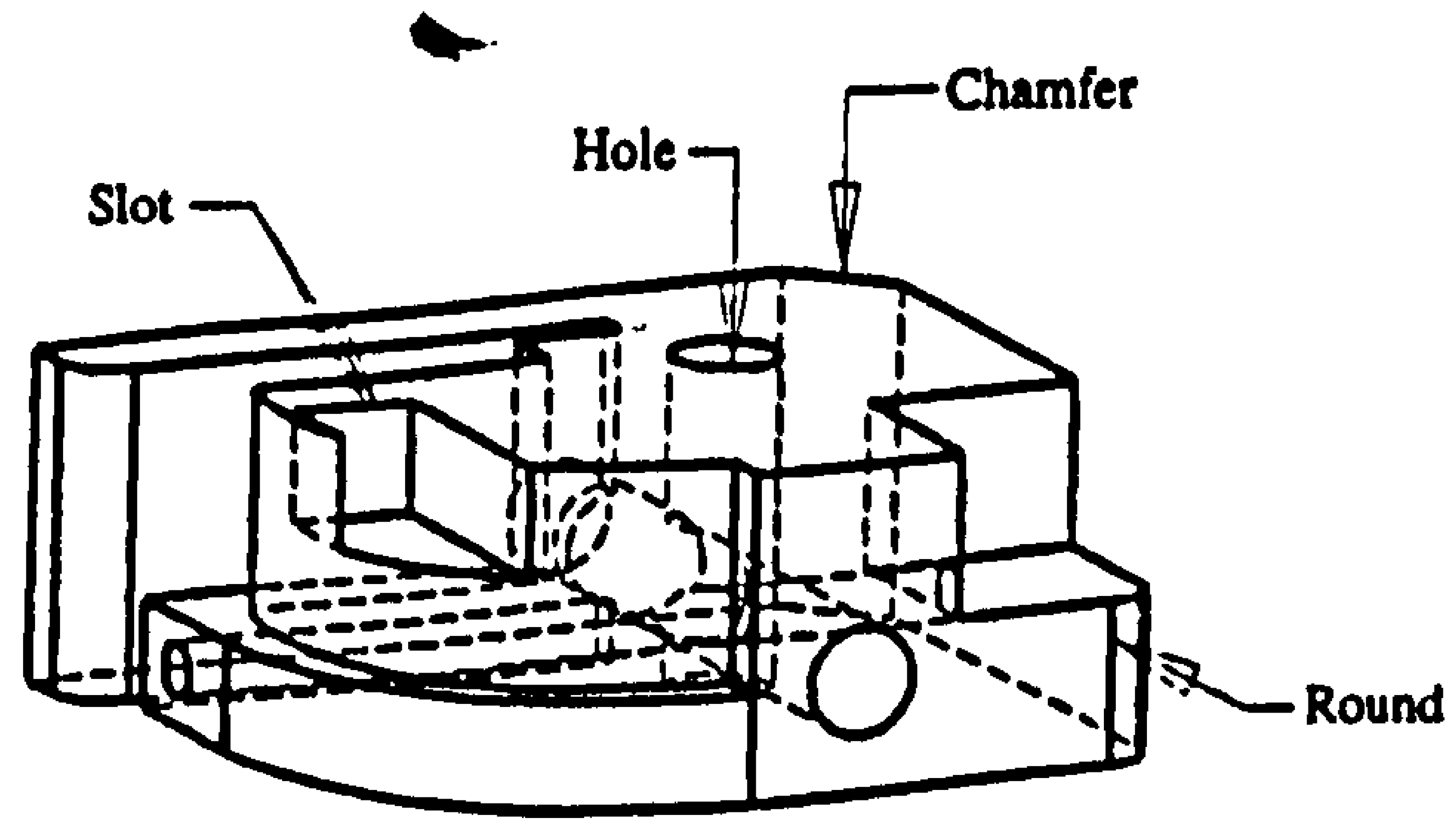

Fig. 2 A part and its form features

convenient for most manufacturing applications. They may be sufficient for tasks such as the computation of areas or volumes, the presentation of geometry or the generation of tool travel paths, but other applications such as cost estimation, design for manufacturability, process planning, etc., require a completely different type of information (7). For instance, in most current process planning systems planners have to describe the topological and geometrical information needed of the feature manually. This technique has been seen as a tedious and inaccurate or inconvenient methodology for today's advanced manufacturing systems like the flexible manufacturing system (FMS). A way to overcome this problem is to implement the automated feature recognition approach to extract the information needed from the CAD database directly. However, in recent years researchers (15, 16) have been trying seriously to overcome this problem by developing a technique for automated feature recognition (AFR) from a solid modeller. This task (AFR) is seen as the most crucial step towards closing the gap between engineering and manufacturing. This research demonstrates a technique for extracting the required features directly from the database of a CAD solid modelling system. The technique has the capability to extract the necessary topological and geometrical information from the solid modeller in an effective and efficient manner. Other information such as the relationships between features are essential for analysing the data using rules. For instance, if the part has two holes, it is very important from the manufacturing process perspective to define whether they are intersecting or one through the other, etc. (Fig. 3a). It is also necessary to indicate the location of the feature on the part for fixturing purposes, particularly if the feature has to be located on a certain slope angle from one of the geometry surface or edge (Fig. 3b). This work is currently under development in order to provide this sort of information.

2.2.1 Feature recognizer

A technique for recognizing various form features and their attributes from a solid modelling CAD system database is discussed in this paper. The CAD system implemented here has a dual solid modeller representation scheme. The first is called constructive solid geometry (CSG) which represents objectives in terms of a combination of primitive volumes such as cylinders, spheres, blocks, tubes, etc., as shown in Fig. 4a. The second is boundary representation (B-rep), which represents the model in terms of topology entities such as loops, faces, edges and vertices which are associated with geometric entities such as curves, surfaces and points (Fig. 4b). In this scheme objects are represented by their enclosing surfaces. For recognizing the feature, the system starts to find a set of faces that have the facts-defined features. These facts which characterize each feature were defined first. The system then matches all the collected entities and their characteristics (types of edges, types of faces, etc.) with the predefined features for defining the feature topologically. Features such as holes, drafts, slots, rounds, etc., have been defined as recognizable topologic and geometric patterns using the boundary representation scheme. The feature recognizer extracts the feature attributes (depth, diameter, distances, etc.) and then sends it to the reasoning system for representation which can then be used for various applications. Figure 5 shows an approach for the proposed automated feature recognition technique.

Above all, a user interface was set up using Pro/Develop (17), the programmatic interface of the Pro/Engineering database provided by Parametric Technology Corporation (see Fig. 6), in addition to bespoke software written for C and UNIX environment. It provides direct access to the database to derive automated feature recognition and enables users to interact with the system easily and efficiently. It also enables designers to create form features such as holes, slots, fillets, rounds and drafts in addition to identifying the geometry and topology of these features, as mentioned previously.

3 THE INTEGRATION OF THE CAD AND THE EXPERT SYSTEM TOOL-KIT

The expert system tool-kit (KEE, or knowledge engineering environment) together with the CAD system (Pro/Engineer) were seen as an ideal medium for achieving the goals of this research. Consequently, the integration between the solid modeller and the reasoning system was considered as an essential task for achieving

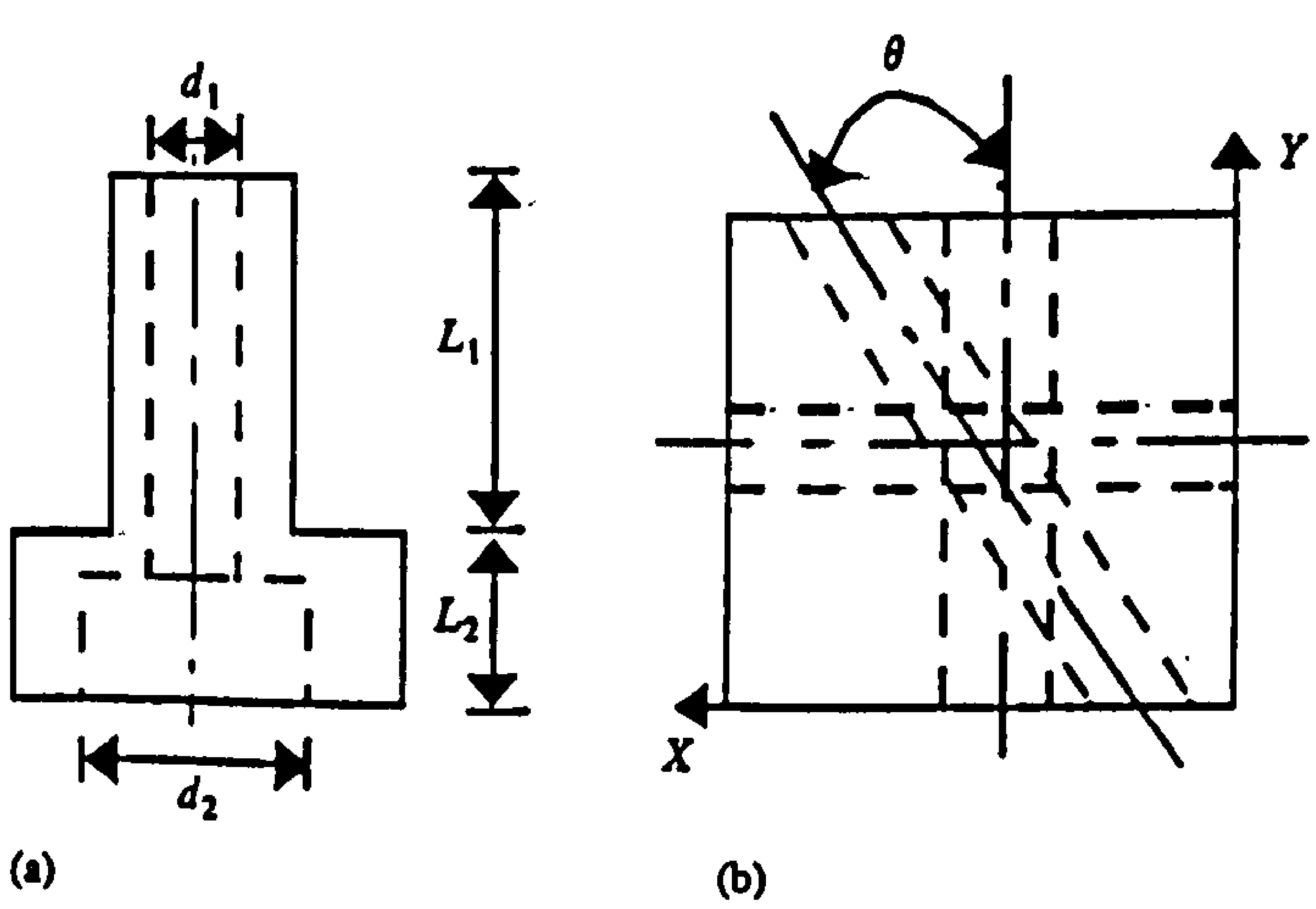

Fig. 3 Relations between features

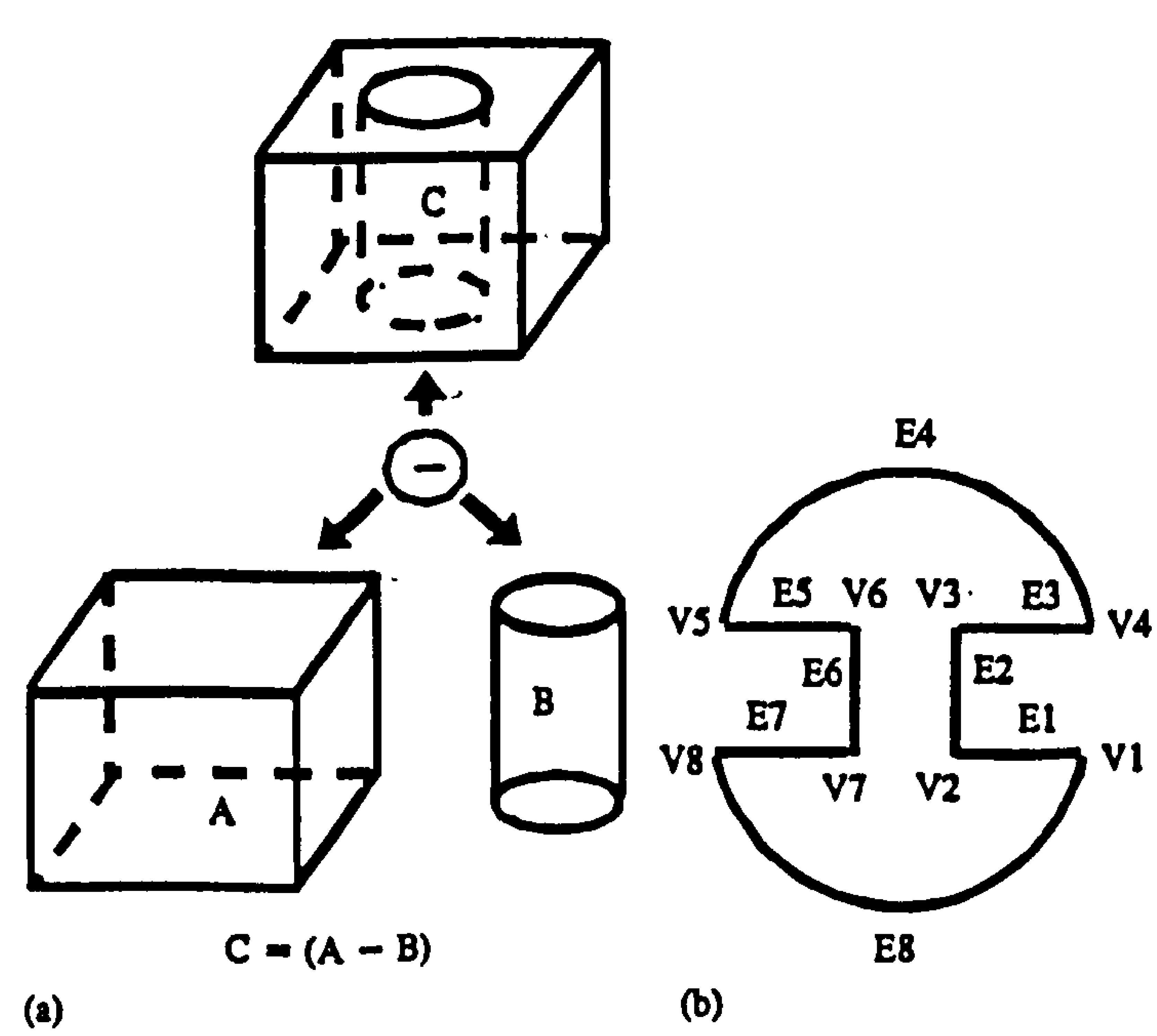

Fig. 4 (a) CSG and (b) B-rep schemes

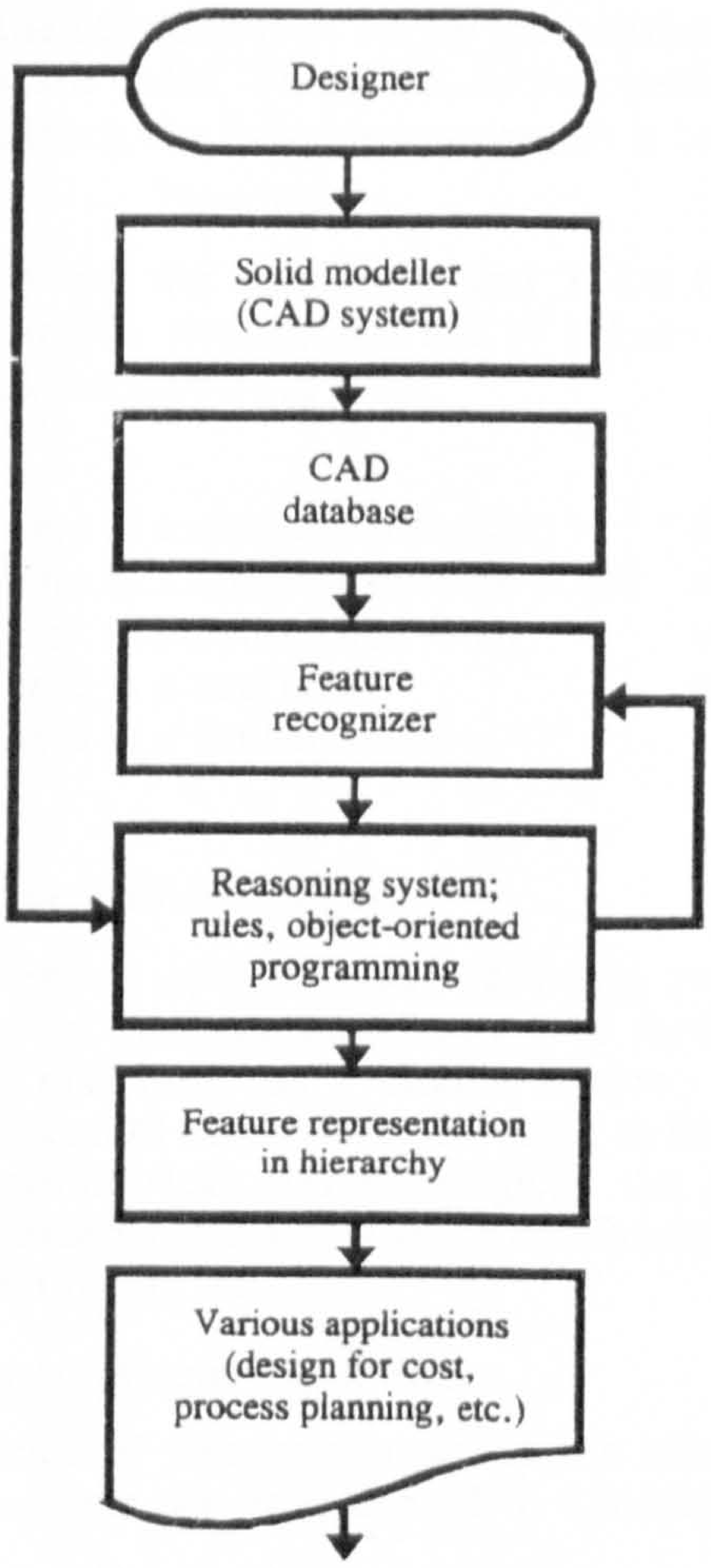

Fig. 5 An architecture for automated feature recognition

the target of this project. KEE itself does not provide an external communication capability but allows complete access to Lucid's Common Lisp language. Common Lisp in turn supports a foreign language interface to communicate with Pascal, FORTRAN and C languages. These external languages can then open, read and write files. On the other hand, Pro/Engineer can communicate with the outside world through the programmatic interface Pro/Develop. Figure 7 illustrates the overall system architecture of the link between the CAD system and the expert system tool-kit (KEE). In a

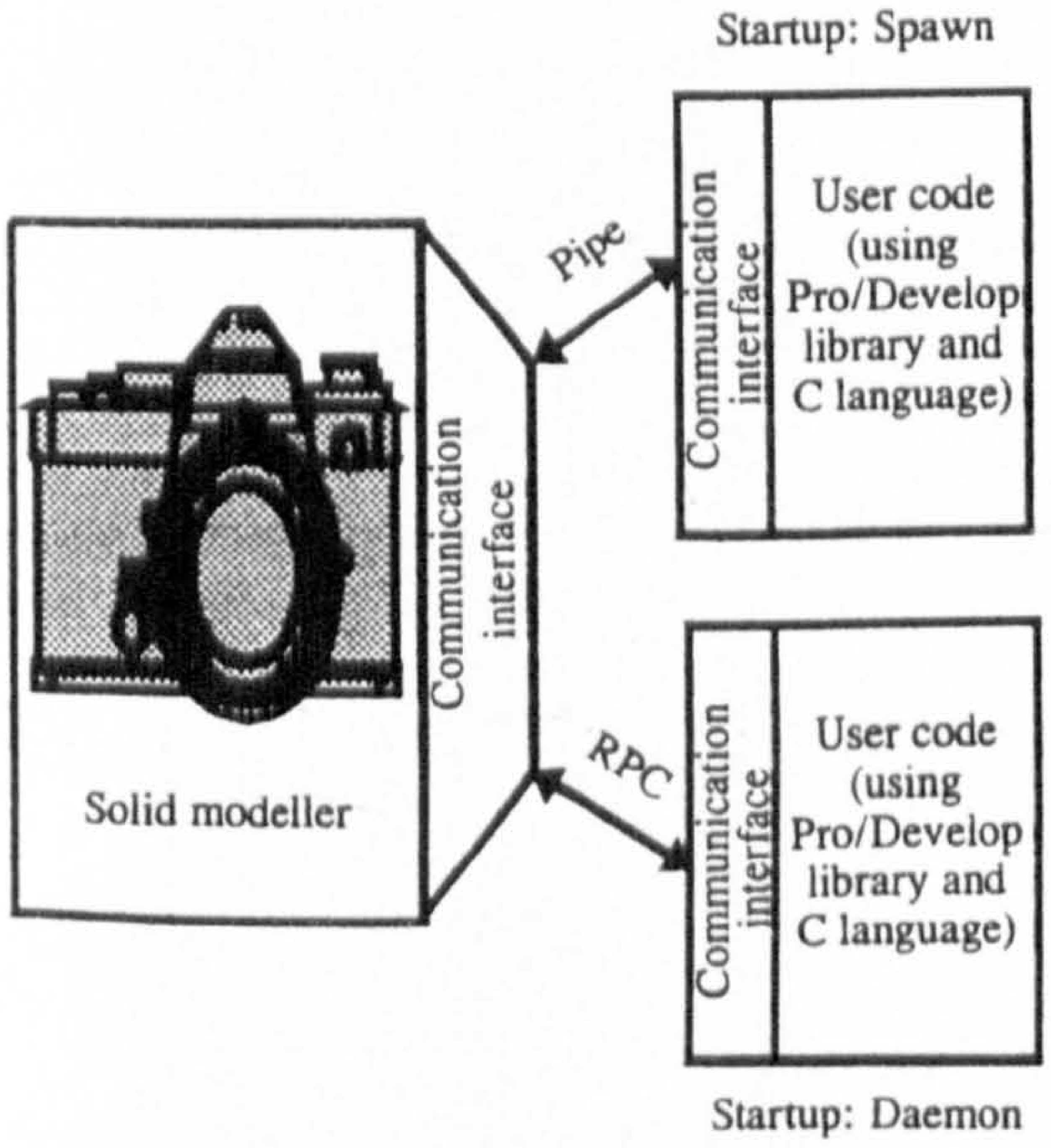

Fig. 6 An interface between the solid modeller and foreign programs (PTC, 1991)

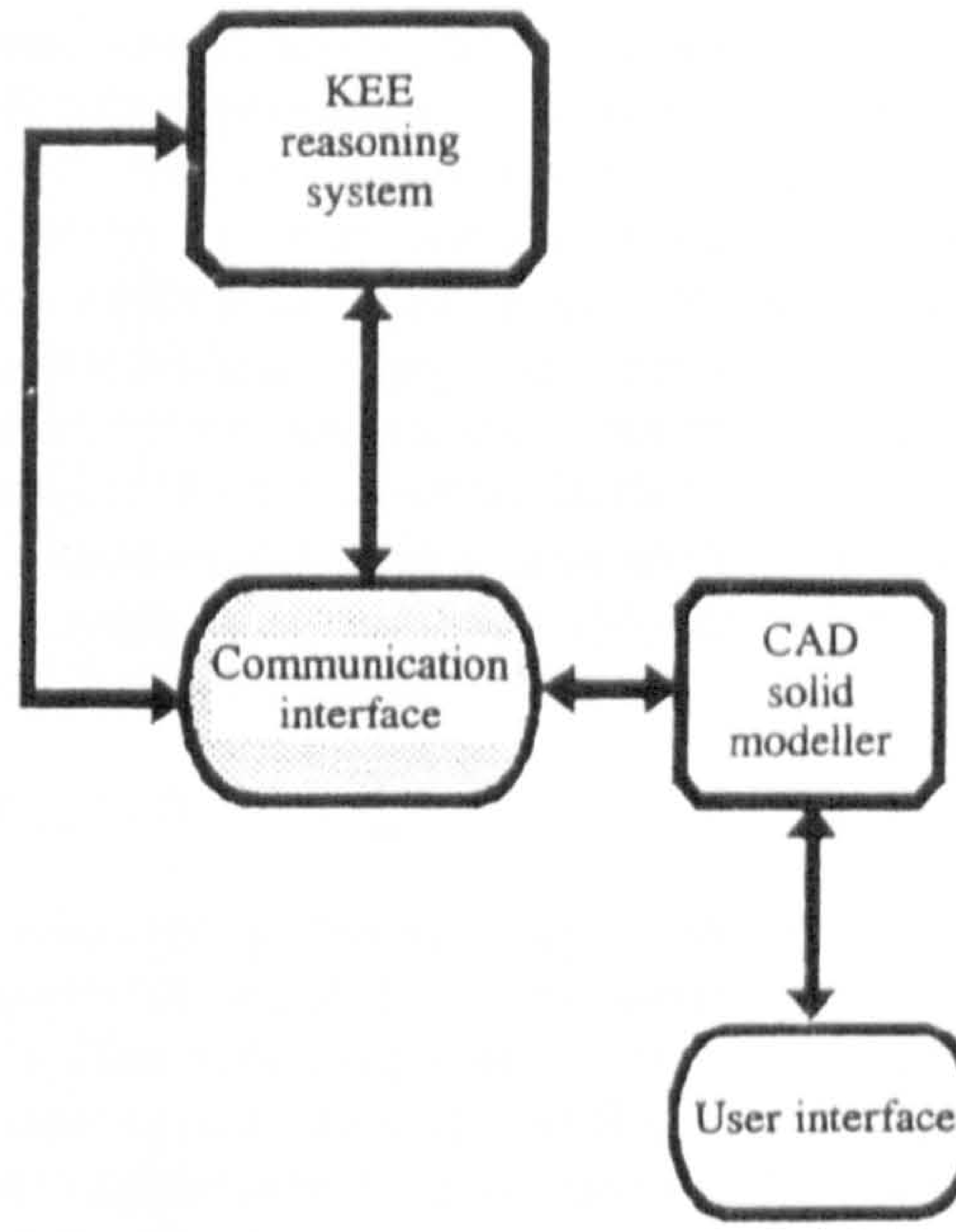

Fig. 7 Overall system architecture of the CAD and expert system communication

typical scenario, when a request for a geometric data query is received, KEE will invoke the proper Lisp method which calls a C routine with a command string as an argument. The C routine then puts the command string in a file and goes into a wait and check cycle until complete information comes back from Pro/Engineer. When the C routine receives all the data requested back from Pro/Engineer, another Lisp program is already loaded, and will immediately start to send the data back to the expert system.

4 THE EXPERT SYSTEM CONSTRUCTION

Expert systems usually contain rules for analysing the part features (topology and geometry), physical characteristics (pressure, temperature, etc.), material, etc. In addition to extensive information about the existing manufacturing facilities, with the aid of the production rules, the expert system can be used as an intellectual information technology (IT) tool for achieving the following CE goals: reducing time to market, reducing manufacturing costs, improving product quality and maximizing product quality and minimizing material and production costs. Details about the proposed expert system construction procedure are discussed in the following sections.

4.1 Knowledge representation

The advent of artificial intelligence systems has introduced a wide variety of knowledge representation schemes such as frames, rules, logical terms, etc. An expert system tool-kit, knowledge engineering environment (KEE), developed by Intellicorp (**18**) was chosen for both knowledge representation and decision making in this research. The system was built on a SPARC Station (SUN4). KEE supports frame-based object-oriented programming and rule-based reasoning. These rules consist of a series of necessary and sufficient conditions. The rules of KEE have been implemented for recognizing the features topologically. For instance, when the conditions of a rule are satisfied then the conditions are valid. Therefore, to recognize the type of a form feature, the following approach is being followed:

If ⟨X⟩ Then ⟨Y⟩

where X are the conditions and Y are the conclusions. For example, the recognition of a hole can be defined through the following rules:

If

(There is a circular top edge) and
(There is a circular bottom edge) and
(There is a cylindrical face) and
(There is a top face) and
(There is a bottom face)

Then

(The feature is a hole)

The expert system rules (recursive rules) have been used for recognizing the feature type (holes, drafts, slots, etc.) by matching the available feature's data with predefined feature characteristics. After defining all the features, geometrical and topological, the system records and represents them in groups according to their types, as shown in Fig. 8.

4.2 Expert system constraints

A number of constraints about the existing manufacturing system are represented in hierarchy using KEE. These constraints are implemented to bound the machining processes and to show the feasibility of the part during the design stage and before making the final prototype. In this context manufacturing criteria have been utilized as rules to approve constraints. Using the manufacturing rules, the designer is able to examine whether the designed part can be manufactured with the available manufacturing facilities or not. For instance, if the designer specifies a hole with a specific diameter (D_h) the system will compare this diameter with the predefined diameter range

$$D_{\min} < D_h < D_{\max}$$

An example of the program is shown in Fig. 9. Warning is given in the case of inconsistency or invalid dimensions (the hole diameter is too big or the hole diameter is too small). Consequently, the designer can select other appropriate dimensions. This can take place at the very early stage when the product is being designed; implementation of this strategy avoids manufacturing surprises.

A set of manufacturing rules and criteria are used to determine machining operations, such as turning, drilling, milling, in addition to non-conventional techniques like electrochemical, laser, etc. An example for selecting the appropriate operation required to make a particular feature according to the predefined rules or constraints is shown as:

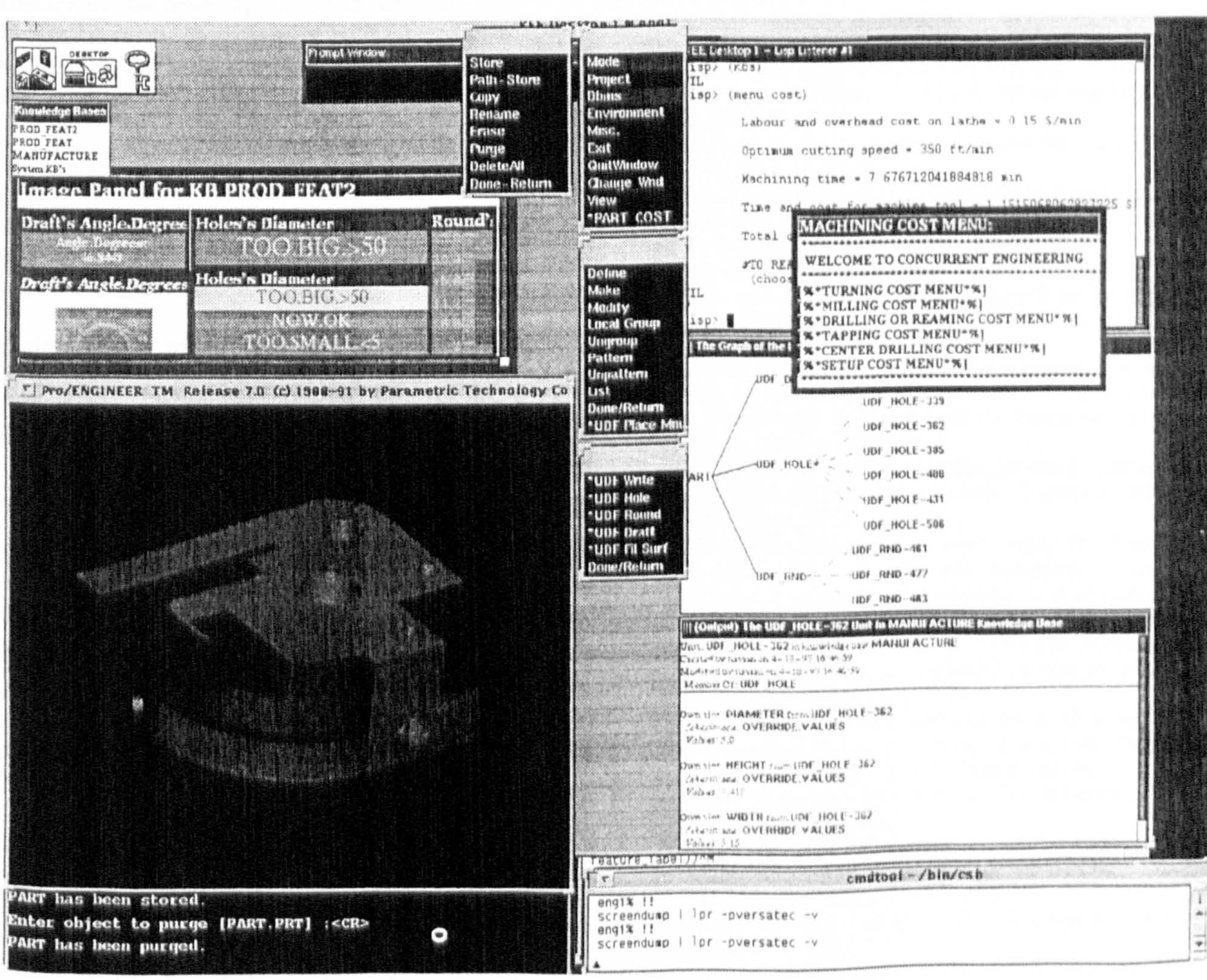

Fig. 8 An integrated CAD and expert system shell

Fig. 9 An example of a design constraint

If

(The feature is a hole)	and
(The diameter of the hole $D_h > 0.01$ inch)	and
(The L/D 'depth over the diameter' < 300)	and
(The tolerance of the hole < 0.005 inch)	and
(Additional rules)	

Then

(STEM is selected)

STEM (shaped tube electrolytic machining) is one of the electrochemical 'EC' drilling techniques that have been accepted practice for a number of years for drilling fine holes.

The most significant benefit of this system is in reducing product cost. After validation of the feature dimensions the system starts immediately to calculate the machining cost of each feature independently. The system then compares the estimated machining cost with the desired one and shows the results. At this stage the designer is able to interact with the system concerning features dimension modification for cost reduction.

5 CONCLUSIONS AND RECOMMENDATIONS

The concurrent engineering approach embodies certain underlying imperatives that help maintain communication between all components of the manufacturing system and permit flexibility to modify the design during each stage of a product's realization. The primary goal of this research is to integrate manufacturing process design and product design to ensure the best matching of market requirements. This integration requires linking CAD/CAM with an expert system toolkit. However, the problem of interfacing CAD with an expert system for design for manufacturability is mainly due to the data incompatibility for the two applications. Therefore the CAD system must be enhanced to provide information about the design features for industrial applications (automation, design analysis, process planning, etc.) in a high level language. This research has produced a feature recognition technique for solving the above problem through defining the information needed at an abstraction level. Moreover, an expert system which contains extensive information about product features and manufacturing facilities has been developed. This system checks the process limits and product feasibility.

This research has emerged and contributed to accomplishing the fundamentals needed for progressing the implementation of design for manufacture; much more effort is urgently required for establishing a general and suitable methodology for industrial practice. Extended work is currently taking place in this project for including technological information such as surface finish, heat transfer, material requirement, etc., which are essential for the manufacturing processes.

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H. Abdalla

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GLOBAL CONCURRENT ENGINEERING

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Abstract. This paper states the main objectives and briefly explains the research work carried out within the IMS Feasibility Study Test Case 3 under ESPRIT project 7752 The collaboration is international and the consortium members represent a cohesive group from the various regions, including companies and research institutions from the US, Canada, the UK, Germany, Italy, Denmark and Finland. The collaborators have been working on a comparative study of Global Concurrent Engineering to find the best practices and major constraints and to design an applicable architecture for a system of global manufacturing. Some of the findings of the research are presented here.

Keywords. Intelligent Manufacturing Systems, Concurrent Engineering, Product Life Cycle, New Product Development, Information Technology, Computer Integrated Manufacturing.

1. PROJECT BACKGROUND

This project describes methodologies for development and manufacturing of products within a Concurrent Engineering (CE) environment, for organisations that operate on a global basis. Globalisation in this context means that the product or different parts of the products can be manufactured in different production sites around the world for a number of reasons, such as technology and resource availability. This necessitates the fulfillment of some requirements as stated by Hayashi (1993): *"a company may have various facilities located around the World and to manage those facilities effectively and to handle its policy making and production planning, a company needs a communications network that interconnects its multiple manufacturing plants and sales offices as well as other facilities."*

The essence of CE is not only the concurrency of the activities but also the cooperative effort from all the teams, which leads to improving company profitability and competitiveness. The measures for productivity are usually based on time to market, product cost, market share, and quality. In reality these factors are interrelated and CE philosophy is to target a mix of all these factors to give an overall framework or strategy to the company. For example, taking into account the design processes, as early as possible during the product life-cycle development, might expose alternative solutions that could provide remarkable quality improvement for an insignificant cost increase.

In this research the definition for CE stated by the US Institute for Defence Analysis (report R-338, 1988) has been adopted, *"Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes including manufacturing and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements".* This definition focuses on the parallelization of the processes during the design stage, but our research considers the globalization as well as the concurrency issues. Further description of the major goals of this project is presented in the following section.

2. PROJECT OBJECTIVES

The goal of this project is to demonstrate the improvement that can be made to global manufacturing capability through the implementation of CE techniques which have been generated, tried, tested and evaluated within companies operating in national and international markets. This project aims to design methods that can effectively support CE for global manufacturing. It is believed that this approach can improve designs, reduce lead times, reduce costs and improve quality to help to ensure the future viability of manufacturing industries in the region. The project objectives were: (i) to establish the extent to which CE is practised; (ii) to identify the critical constraints with respect to global manufacturing in terms of technology, technology management and human resources; (iii) to synthesise the best practices of CE and to diminish the effects of the critical constraints; (iv) to design an architecture of a CE System for global manufacturing, which represents a model of the functional activities; and (v) to disseminate the results through a Global Concurrent Engineering Workshop. The research work was carried out by researchers from a number of organisations within the EU, the US and Canada as part of the IMS feasibility study as shown in Fig. 1.

California Polytechnic State University, US
Carleton University, Ottawa, Ontario, Canada
De Montfort University, Leicester, UK
Nokia Corporation, Finland
North Carolina State University, Raleigh, US
Northern Telecom*, Ontario, Canada
Odense Steel Shipyard, Denmark
Syntax Sistemi Software, Italy
Technical University of Denmark
TransTec**, Birmingham, UK
VTT Research Laboratory

* International Coordination Organisation
**European Coordination Organisation

Fig 1. IMS Test Case 3 Consortium Members

3. THE IMS GCE PROJECT STRUCTURE

The project work programme is undertaken through five work packages. Four of the work packages are directly related to the stated objectives and the fifth work package is the project mangement, which controls and co-ordinates the total project, as shown in Fig. 2.

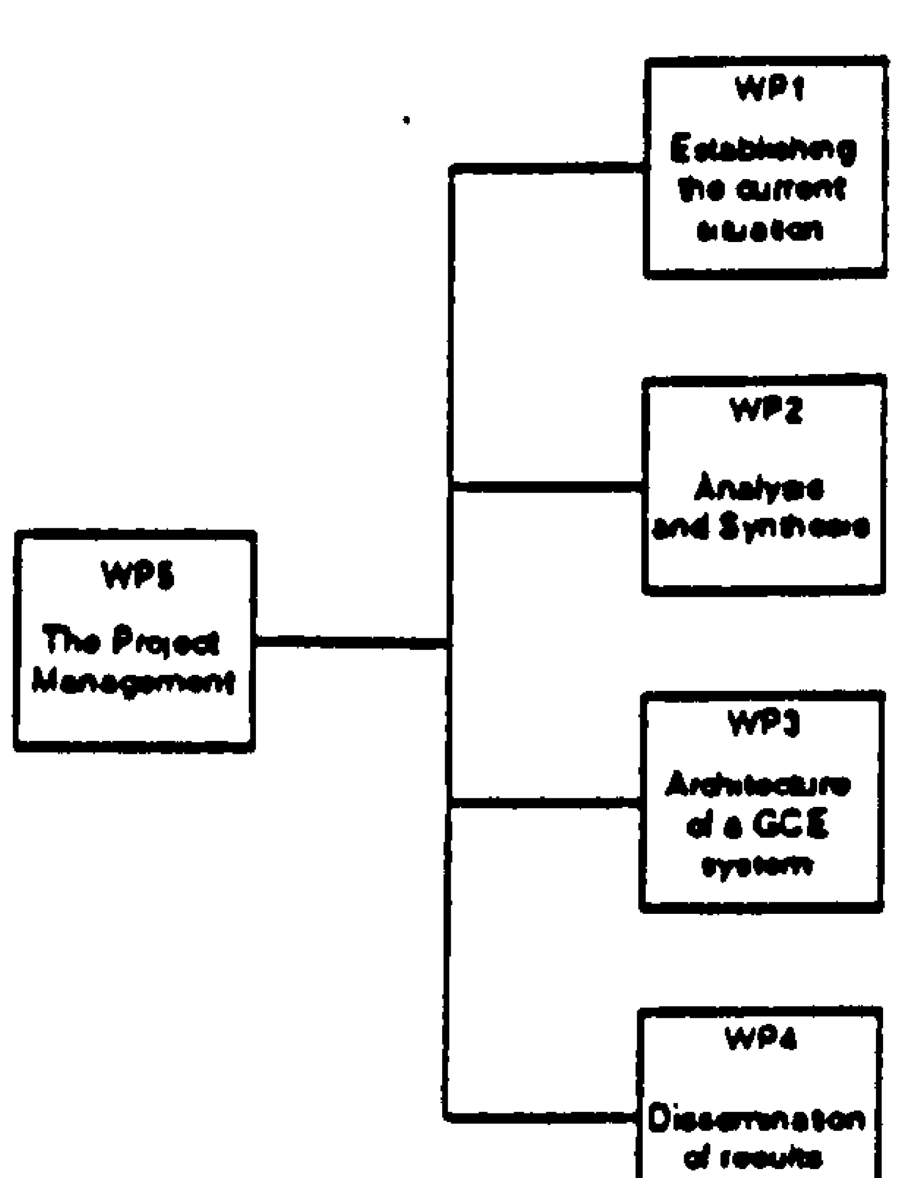

Fig 2. The IMS-GCE Project Structure

4. RESEARCH METHODOLOGY

A worldwide survey was carried out in order to provide the information needed to define the best CE pracrice and to build the GCE architecture. Over 300 companies were identified, but only 150 were approached as suitable candidates to participate in the GCE survey. The selection of these companies was based on two main factors, first these companies are practising concurrent engineering strategy and secondly, these companies are actively manufacturing and marketing in a number of countries. After the identification of the companies a questionnaire was developed to collect the data needed for the research. The Questionnaire was designed to address a wide range of issues to establish how GCE is exercised in those organisations participating in this research. They were also designed in such a way as to allow examination of different factors for NPD activities. To ensure that suitable feedback is achieved well defined, logical and quantitative types of questions were included in the Questionnaires.

The questionnaire, as shown in Fig. 3, consists of three parts: corporate, management and psychological.

The corporate level is addressed by a questionnaire aime to examine corporate policies, strategies and practices in the implementation of GCE and the organisation of product development in the company. The second level of analysis examines the relationships between management and project teams. This level of analysis focuses on factors determining the effectiveness of GCE practices at the development programme and project level. It surveys project team leaders, design and manufacturing team members and managers working directly with project teams. The third level of analysis, the infra-project level, examines the internal operation of the teams. These issues focus on the R&D design and manufacturing interaction on the teams and their locations. It also examines the teams satisfaction issues.

The strength of the IMS GCE research concept is that it allows for the linkage of these three levels of analysis within each company. Corporate or business unit strategies and policies can be linked directly to project team decisions and processes, which can be directly linked to measure team satisfaction, cohesion and commitment. It allows for the hypotheses concerning the relative merit of different CE strategies and policies in influencing the outcomes of specific development projects, both in terms of meeting business goals and in terms of worker and management satisfaction with the development process.

A brief description of the methodology of this research is shown in Fig. 4. The analysis of the data collected from the Questionnaire was used to provide a guide for the best practice in implementing GCE and also to identify specifications and requirements to develop an architecture for GCE.

5. BENCHMARKING STRATEGY

The essence of benchmarking is based on competitive performance according to other external perspectives. It is the process of comparing business practices and performance levels between companies in order to gain new insights and to identify opportunities for making improvements. The greatest benefit is likely to be achieved by focusing on those areas of the business that are critical in driving competitive success. Emphasis is placed on understanding the processes that deliver performance and best practices in relation to those processes. Benchmarking helps to set strategy and identify new techniques. It also maintains the stimulus for continuous improvement. The key for best benchmarking practice should emphasise an understanding of the actual performance of the business rather than just comparing results.

The collected data could be analysed to identify differences in performance levels and practices according to the following benchmarking criteria:

* Generic benchmarking: investigating the strategy and practices of businesses in order to understand and learn from their experience.

* Functional benchmarking: which compares similar functions in different industrial sectors such as the manufacturing or the design process in Automotive, Aerospace, Telecommunications etc.

* Competitor benchmarking: which is a comparison between functions or performance and practices in similar industries. For instance, the current NPD strategy from two companies in the same sector.

This research concentrates on Generic Benchmarking because of it is believed it would provide a general outlook for many industry sectors and various companies.

5.1 The Main Findings of the Benchmarking

In this paper samples of the benchmarking results are presented. The steps and methods which are adopted by companies practising CE strategy are reviewed. The benefits, and the barriers, of implementing CE are also given.

Steps taken for implementing CE. Due to the diversity of the industrial sectors involved in the survey, in terms of product nature, size of the company, and its objectives, and the steps taken to implement CE varied from one Company to another. Figure 5 shows the various common steps taken by the companies towards implementing CE. Training for staff was regarded as the most vital step and ranked first with 56% of the companies indicating the importance of this factor. The management structure of 52% of the companies had to be reorganised in order to utilise CE. Functions co-location was considered by 44% of participating companies as the initial step. IT tools were used by almost 30% of the companies to support CE, but it did not prove to be the strongest factor as some might have expected.

These results are similar to findings of the UK Design Council Survey where more than 50% of the organisations used product teams and co-located their team members in order to achieve better communications and decision making ability.

Barriers to CE Implementation. The main barriers reported during the changes to CE were management problems (41%) and resistance to change (41%) as shown in Fig 6. Poor definition and lack of expertise or information were highlighted by 33% of the companies as major difficulties to persuade employees of the concept. Again similar outcomes were stressed in the UK Design Council's survey where 70% of the companies participated in that survey mentioned that lack of CE information and difficulty in knowing where to start as crucial barriers to CE implementation. These results emphasise the necessity for training management as well as other employees to achieve a clear understanding of the philosophy.

In the IMS TC3 survey 41% of the companies indicated that lack of training was a major obstacle. On the other hand, companies which have been practising CE have focused on team building skills and the use of TQM, and quality function deployment, the techniques which entail the involvement of customers and suppliers as principal players with a key role in the success of the business. However, lack of tools was hardly mentioned as a barrier as only 4% of the companies reported that as a problem in implementing CE. This means that CE implementation requires changes in the organisational managerial and cultural aspects as well as technical.

Benefits of CE. Significant CE benefits were reported in the questionnaire as shown in Fig. 7. The most remarkable benefit reported was shorter time to market (70%). In addition to other benefits such as:

* improving communications (59%)
* improved product quality (56%)
* reduced development costs and better management (33%)
* reduced design change (48%) which means shorter ramp-up time and improving the company's competitiveness. The Design Council Survey 1993 has also shown that late design changes can seriously affect development costs, as they are probably the most expensive to implement.
* CE also increased the profit of 30% of the companies.

The above benefits are interrelated and lead to other achievements such as increasing marketshare, and customer satisfaction.

6. ARCHITECTURE FOR GCE

One of the objectives of the project is to develop an architecture or description model on how to design a product within Global Concurrent Engineering environment. The proposed architecture is applicable to various types of industrial sectors. It is based on the CIM-OSA model and modern systems theory. The CIM-OSA model is structured on three main dimensions: (i) the life-cycle dimension in terms of design requirements and implementation (ii) the dimension concerned with the degree of particularisation called the dimension of generality, which is divided into three levels, generic level, partial level, and particular level (iii) the dimension of structure and behaviour which is named as the dimension of views. This dimension implies functional, informational, resources and organisational views. The input to all these components were mainly from the results of the data collected from the companies, which gives full insight of what companies are doing and need.

The life-cycle dimension. The life-cycle dimension of the CIM-OSA architecture includes phases as follows:

Phase 1:	problems analysis and detail design
Phase 2:	construction and integration
Phase 3:	preliminary and detail design
Phase 4:	control, maintenance and support
Phase 5:	implementation and carrying through the operational system

The above phases considered here are basically the analysis, design and construction of the global concurrent engineering system rather than the life-cycle of the product created in the global concurrent engineering system.

The dimension of views. the dimension of views encompasses a set of views, such as functional views and their interdependence, an information view, a resource view, an organisational view, and cultural views. The CIM-OSA architecture is extended to include the cultural view in order to adequately describe the GCE application. Also in the CIM-OSA model the functional view includes a modelling of tasks and dynamic behaviour as one component. The proposed architecture for GCE deals with these two views separately to emphasise the importance of each view. For further detail refer to ESPRIT Project 7752 Deliverable 3.2.

Main components of the Architecture. The architecture consists of three major levels, each level including two sub-architectures, one procedural focuses on how things can be done, and the other on configurational and solution oriented to illustrate potential system solutions. Above all functional and dynamic views were considered in order to create a platform to the architecture. In addition to the cultural view to supplement the organisational view in order to analyse the cultural factors of GCE. The model has also a mode of inquiry dimension which is applicable to various views and particularly the cultural, the organisational and the resource view. Further detailed study is required to explain fully how the proposed architecture could be implemented with specific company considerations.

7. CONCLUSIONS

The value of implementing CE is confirmed from the findings of the IMS-TC3 Questionnaire. Companies practising CE, especially if they are manufacturing goods in multi-site locations, will benefit by reducing time to market, reducing product cost and increasing product quality. This in turn will result in improved profitability and competitiveness which are naturally the main objectives of any organisation.

The research reported here was conducted by researchers in various countries representing organisations and research institutions from varied backgrounds and of differing size. A comprehensive questionnaire was developed and many organisations were interviewed. Data was collected and analysed to extract best practices for the implementation of concurrent engineering in global manufacturing. The collected data was also used to define specifications and requirements to establish an architecture based upon CIM-OSA framework was developed.

This work is part of a feasibility study which is likely to lead to a full scale investigation. This paper is intended to give a brief outline of the research carried out as it is not possible to provide a full and detailed account of the work.

8. ACKNOWLEDGEMENTS

This paper describes the collaboration research carried out by Test Case 3 of the IMS Feasibility Study Consortium members. The list of organisations who participated in this work is given in Fig. 1.

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The efforts of Mrs M Sims and Mr M Greenaway in preparing this paper are very much appreciated.

9. LIST OF ABBREVIATIONS

GM	Global Manufacturing
GCE	Global Concurrent Engineering
IMS	Intelligent Manufacturing System
IT	Information Technology
NPD	New Product Development
TQM	Total Quality Management

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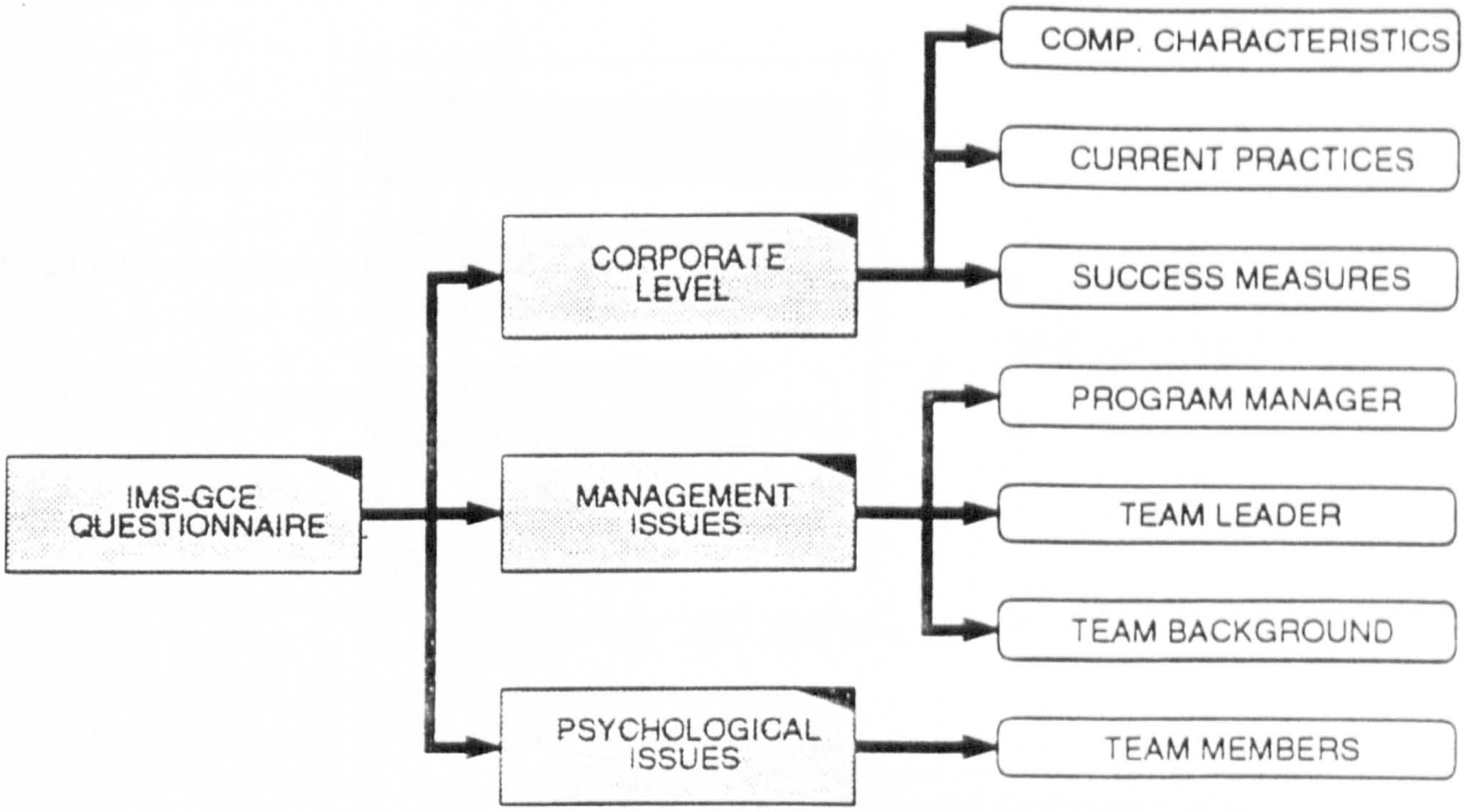

Fig. 3 IMS GCE Questionnaire

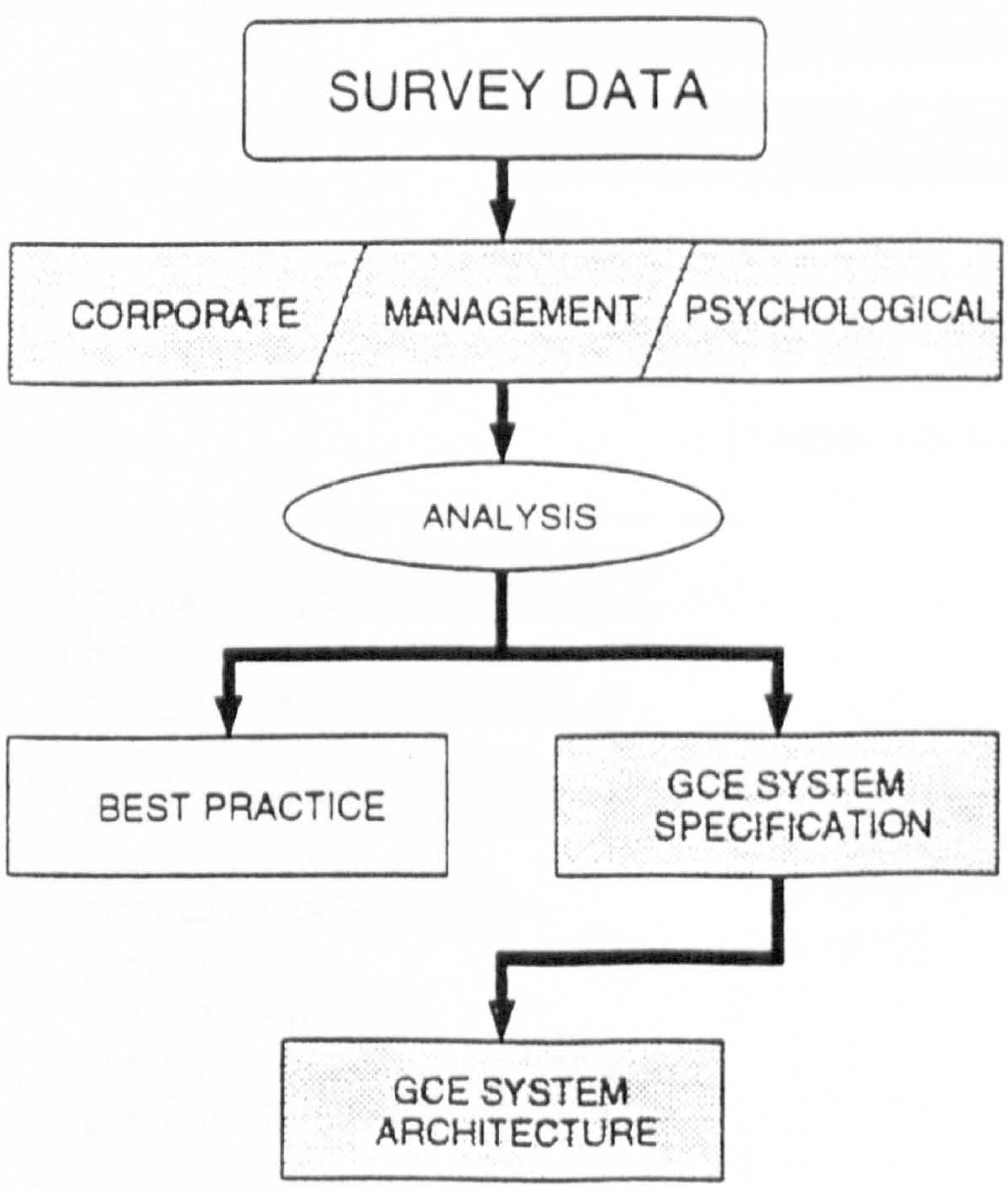

Fig. 4 Research Methodology

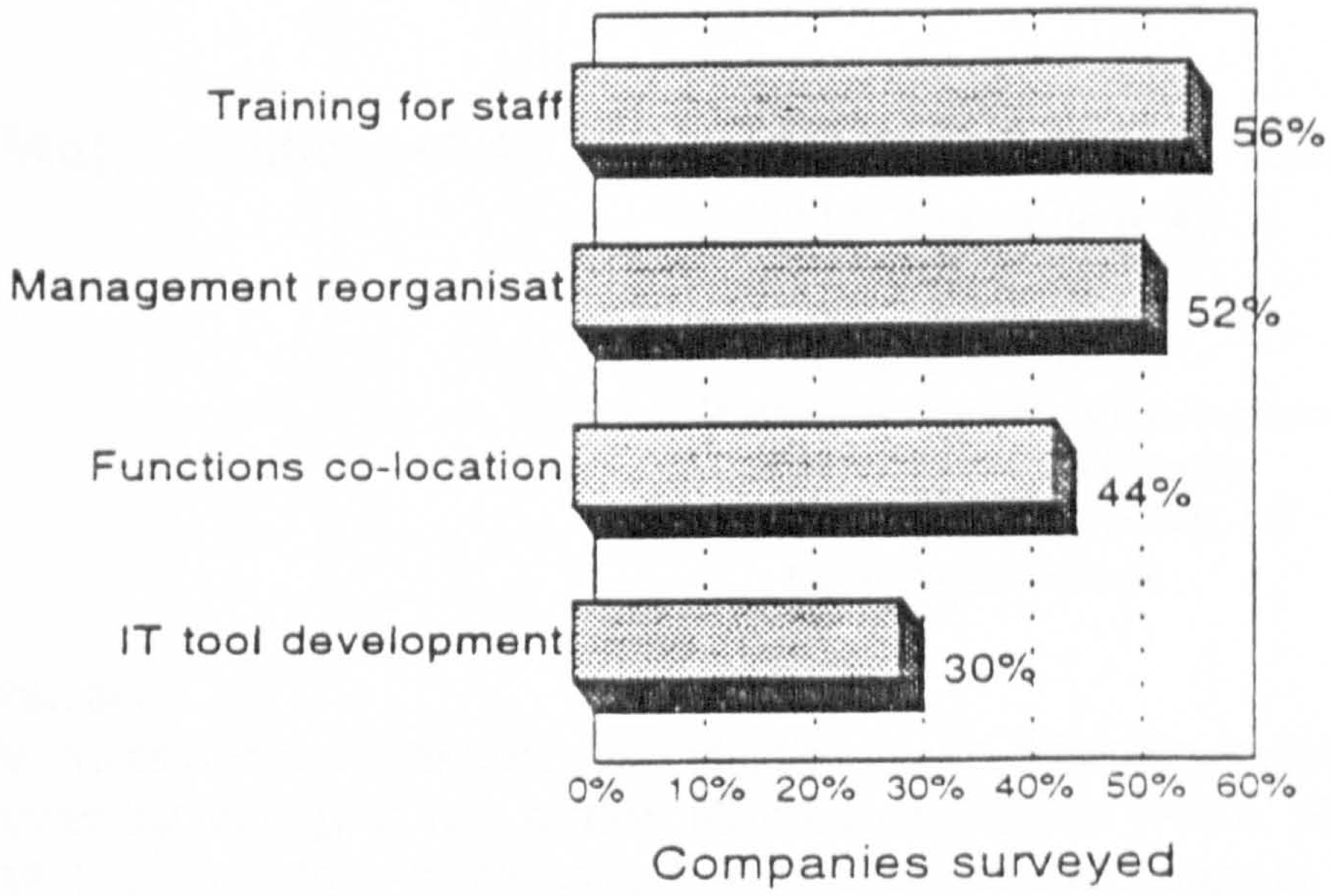

Fig. 5 Steps taken for implementing CE

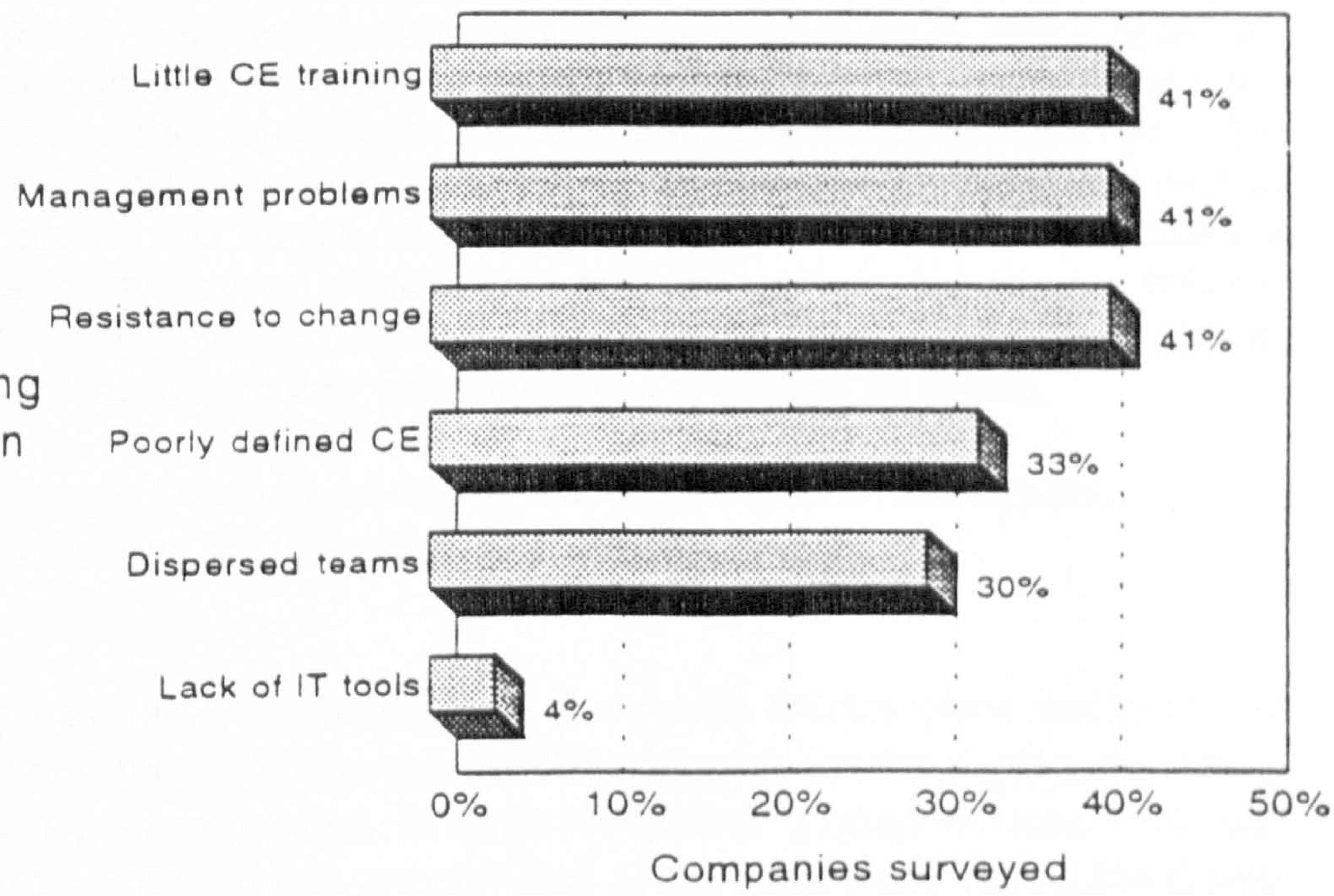

Fig. 6 Problems encountered during the implementation of CE

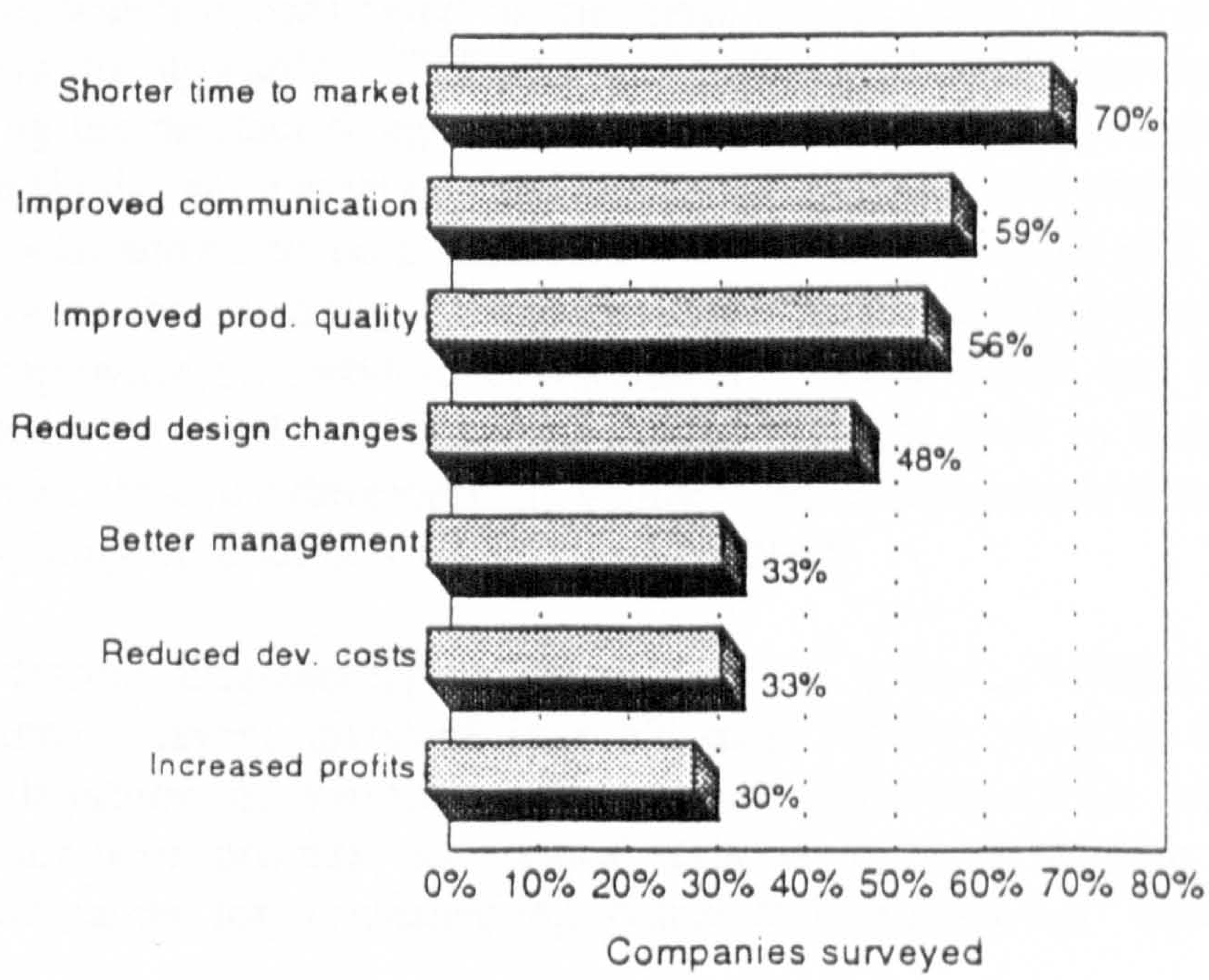

Fig. 7 Benefits gained after the implementation of CE

Major Findings of An International Collaborative for Global Manufacturing (IMS Test Case 3)

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Abstract
The dynamic change of technologies and global market demands necessitates the utilization of a Concurrent Engineering strategy in new product life-cycle development (NPD). NPD practices play an increasingly critical role in company performance. It is more complex than it appears, especially with the current trend by major organizations to expand operations in other countries in response to economical considerations. Despite the availability of modern technology and effective management strategies, companies are still losing out as a result of outdated development practices. This paper presents the state of the art and major findings of a world wide benchmarking exercise carried out within the multi-national collaborative programme (IMS). The consortium members represent a cohesive group from various regions, including companies and research institutions from the USA, Canada, and Europe. The study covers several industrial sectors including automotive, aerospace, telecommunication, shipbuilding and information technology. Effective communication; a systematic involvement of customers and suppliers; flow of information between departments and effective use of modern technology were reported as key elements for success.

Keywords: Organisational strategy, Communication infrastructure, culture, customers, suppliers, functions co-location, Multi-disciplinary teams, benchmarking, CIM.

1. Background
The complexity of today's product requirements in the world market place increases the pressure on companies to implement effective and efficient methods for developing, designing, manufacturing, and marketing their product, in terms of greater quality, reduced cost, and greater customer satisfaction. These factors are pertinent to decisions made during the design stage, which is considered as the most critical stage in the product life-cycle. Research has shown that upwards of 70% of a product's manufacturing cost is committed by decisions made during the product design stage (Young, et al 1992). Decisions made at this important stage have significant impact on final product cost and time to market. Concurrent Engineering (CE) has been shown to be a successful way of achieving the goal "get it right first time". It is a customer driven strategy which encompasses a combination of philosophies, and tools aimed at improving the product development process. There are spin-off benefits which can be gained as a result of implementing CE strategy, such as increasing market share, reducing product life-cycle development, shorter lead time, expanding the product range, and improving the quality of both new and existing products.

Concurrent Engineering philosophy utilizes a cross-functional team approach to get the pertinent players involved in each stage of the product development cycle. Therefore, parallelisation of various activities, data standardization, and integration of the product development process are critical criteria in implementing CE. Some of the principal requirements for implementing concurrent engineering strategy have been discussed by

(Parasad, et al 1993). Their approach highlights the possibility of collaborating designers to proceed independently, correlate interdependency, use existing information (data, knowledge, and processes), in addition to negotiating conflicts arising from design inconsistencies. Their work raised a series of research issues which need to be addressed to affect the practice of CE. Working relationships between people was identified as one of the main imperatives for implementing CE. Extensive training in team building, leadership, and the CE plan prior to actual start were some of the lessons learned from the implementation of CE at OECO Corporation, USA (Monroy, 1992). Benefits reported were significant, an overall lead time reduction by 50%, reduction in engineering changes by 40%, reduced unit costs, and general improvement in the product quality and reliability. Burhanuddin and Randhawa, 1992, have described a system that integrates product design specifications with material and process databases, and a simulation based analysis module. Their system allows product designs to be evaluated economically and technically, and to identify the best production environment. Sutherland et al 1988, proposed a methodology for a CE strategy which incorporates machining process modeling and the design of experiments to find robust product/process design in terms of a set of factors such as part material and machining conditions. Abdalla and Knight 1994, developed a paradigm which encompasses an integrated solid modeling and knowledge-based system for supporting concurrent product and process design. The system includes a constraint knowledge-base that has the capability to monitor the design consistency as the design progressing.

This paper illustrates the frame work of a world wide benchmarking exercise which covers large, small to medium-sized enterprises in various industrial sectors from different geographical locations across the world, as shown in figure (1). The results have enabled the authors to specify key elements of a good GCE practice. The benchmarking exercise has proved that co-ordination between the various business functions and the translation of customer requirements into physical reality are crucial for international competitiveness. The goal is to achieve rapid product realisation through customer-driven designs and agile manufacturing. Companies need to built up on reputation for quality and reliability products and establish continuous improvement based on technological innovation. The results indicate that product innovation has repeatedly become important again in mature sectors, such as Automotive, Aerospace, Telecommunications, Consumer electronics, Computer equipments, Machine tool equipment, and Ship-building. Traditionally, the focus was on process innovation and efficiency of production rather than new product development.

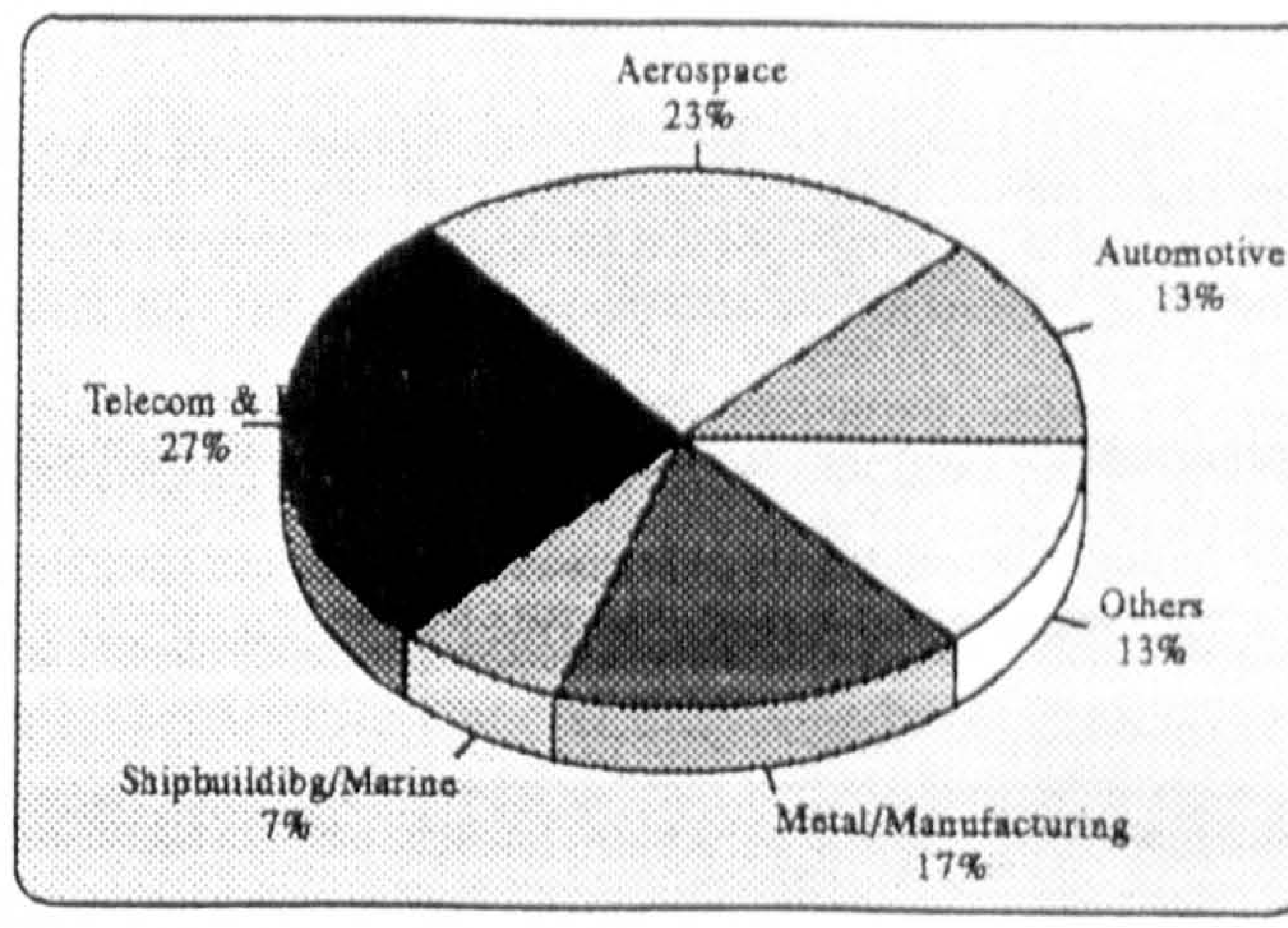

Figure (1) The Industrial Sectors Participated in the Benchmarking

2. Project Objectives

The project aims to design methods that can effectively support Concurrent Engineering for Global Manufacturing. It is believed that this approach can improve designs, reduce lead times, reduce costs and improve quality to help to ensure the future viability of manufacturing industries in the region. The project objectives are: (i) to establish the extent to which Concurrent Engineering is practiced; (ii) to identify the critical constraints with respect to Global Manufacturing in terms of technology, technology management and human resources; (iii) synthesize the best practices of Concurrent Engineering and to diminish the effects of the critical constraints; (iv) to design an architecture of a Concurrent Engineering System for global manufacturing, which represents a model of the functional activities; and (v) to disseminate the results through a Global Concurrent Engineering workshop.

3. Methodology

A methodology was developed to achieve the aims and objectives of the project, as shown in figure (2). Over 320 companies were identified, and from those 150 distinguished organizations and companies were approached as suitable candidates to participate in the study. The selection of 150 companies was based on two major factors; firstly these companies are currently implementing the philosophy of Concurrent Engineering and secondly, they are actively manufacturing and marketing in a number of countries (world class). Questionnaires were developed and designed so as to address a wide range of issues to establish how GCE is exercised in various organizations. The questionnaires were designed in such a way to allow examination of different factors for New Product Development Projects. They were organized into three sections: (i) Corporate level; (ii) Management issue; and (iii) Psychological issues, as shown in figure (3). The corporate level was addressed by a questionnaire developed and managed to examine corporate policies, strategies and practices in the implementation of GCE and the organization of product development in the company, as indicated in figure (4).

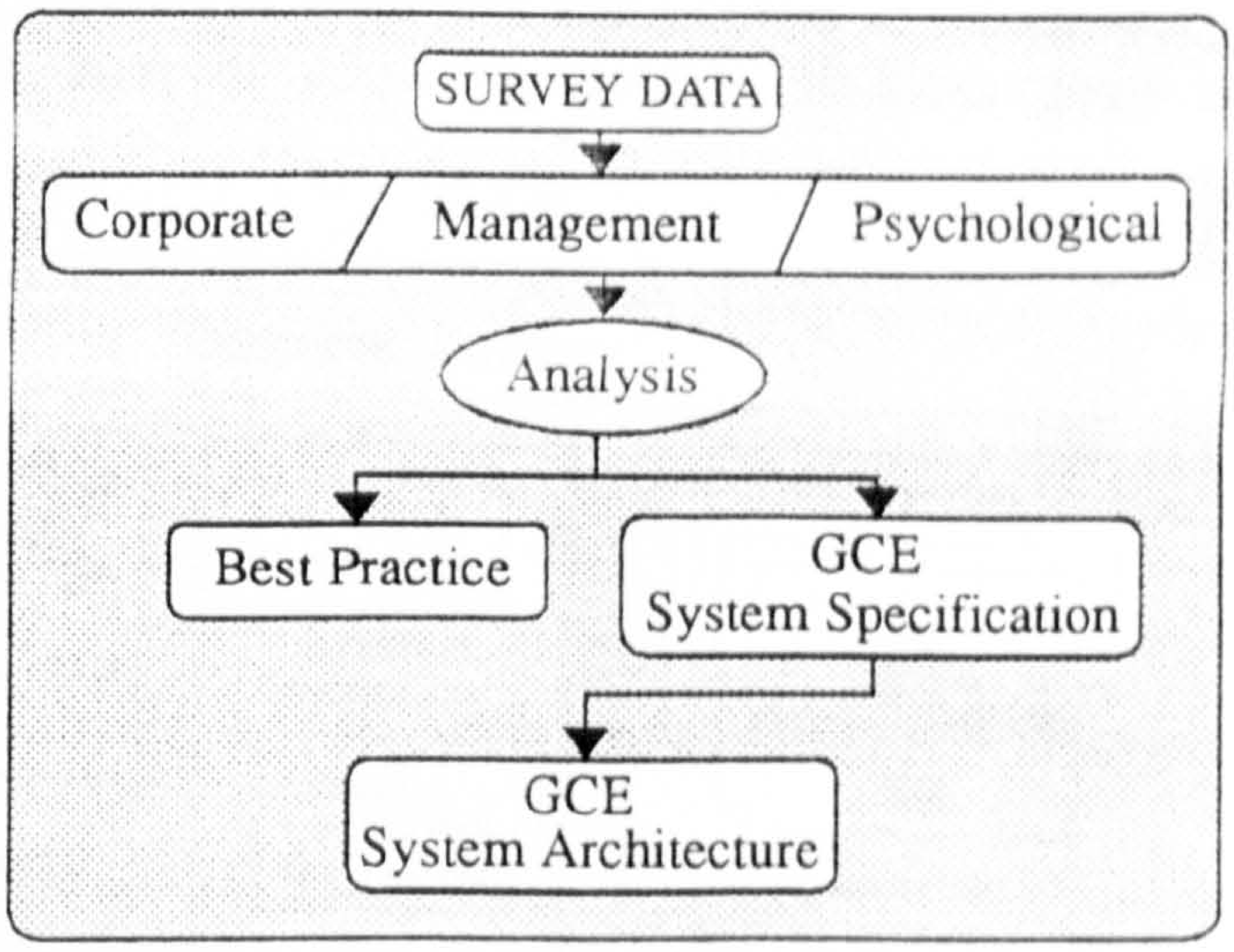

Figure (2) Research Methodology

The corporate level survey was directed towards senior management. The second level of analysis examines the relationships between management and project teams. This level of analysis focuses on factors determining the effectiveness of GCE practices at the development program and project level. It surveys project team leaders, design and manufacturing team members, and managers working directly with project teams. The third level of analysis, the infra-project level , examines the internal operation of the teams. These issues are focusing on the R&D/Design,

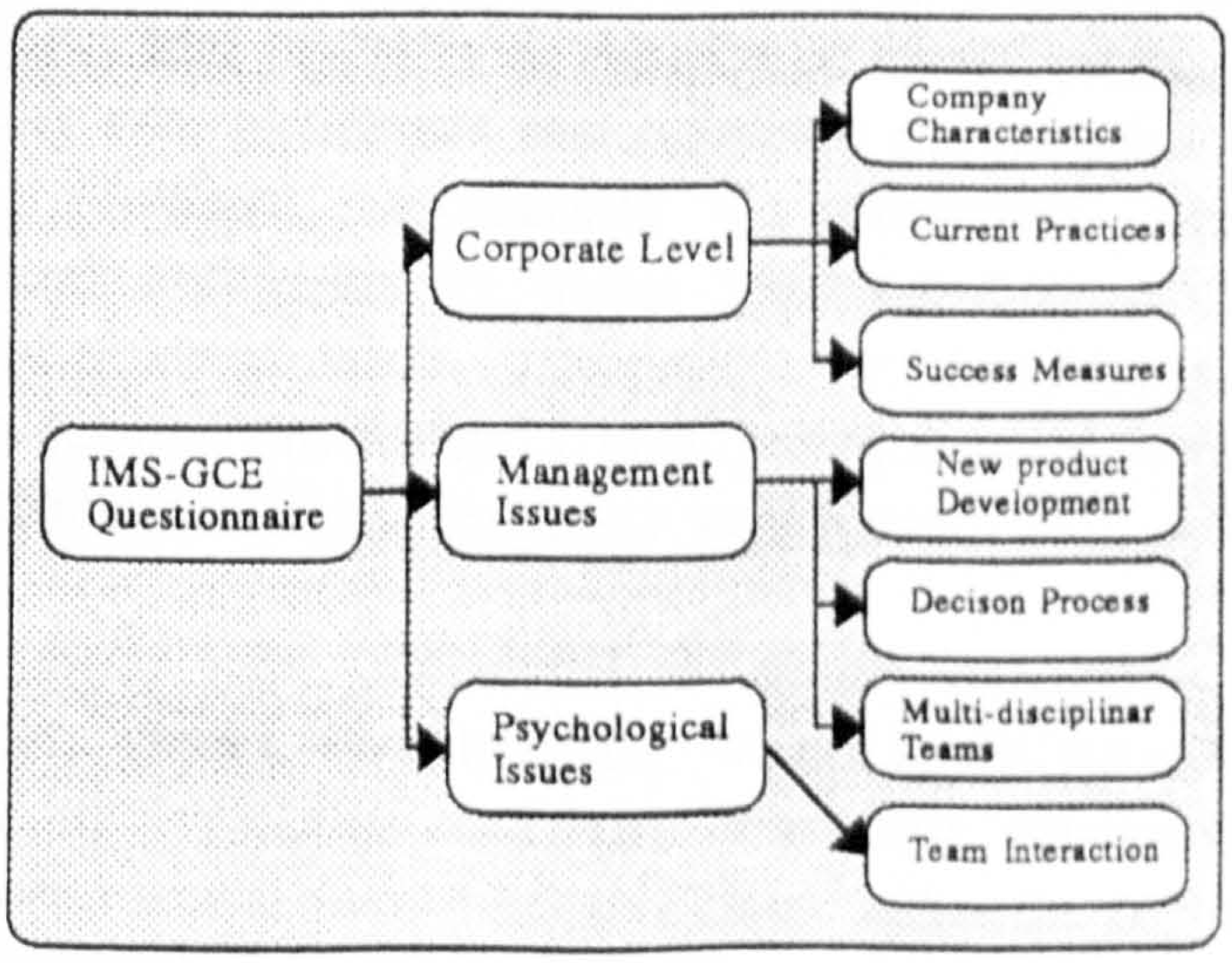

Figure (3) IMS-GCE Questionnaire

manufacturing interaction on the teams and their locations. It also examines the team's satisfaction issues.

The strength of the GCE research concept is that it allows the linkage of the three levels of analysis within each company. Corporate or business unit strategies and policies can be linked directly to project team decisions and processes, which can be directly linked to summary and individual measures of team satisfaction, cohesion, and commitment. This design is based on a Global Concurrent Engineering approach which is multi-level and comprehensive. It allows for the hypotheses concerning the relative merit of different CE strategies and policies in influencing the outcomes of specific development projects, both in terms of meeting business goals and management satisfaction with the development process.

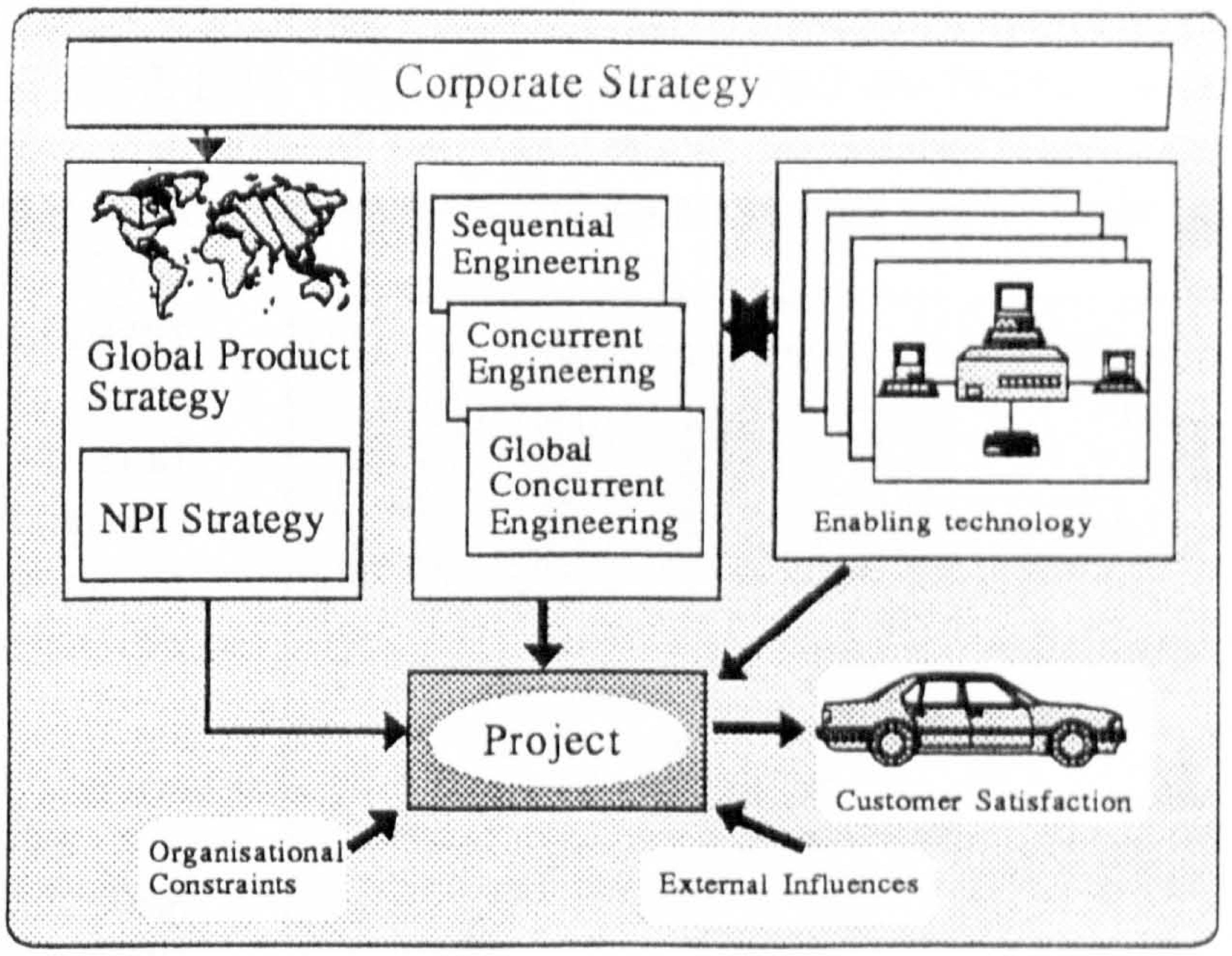

Figure (4) A Corporate Strategy of A Product Development

4. Benchmarking Strategy

The essence of benchmarking is based on competitive performance according to other external perspectives. It is no longer limited only to comparison against competitors, but also aims to gain competitive advantage. It is the process of comparing business practices and performance levels between companies in order to gain new insights and to identify opportunities for making improvements. The greatest benefit is likely to be achieved by focusing on those areas of the business that are critical in driving competitive success. Emphasis is placed on understanding the processes that deliver high performance and best practices in relation to those processes. Benchmarking helps to set strategy and identify new techniques and maintains the stimulus for continuous improvement. It also addresses problems encountered by companies during implementing new technology and techniques and leads to better understanding of the customer expectations; fewer complaints and more satisfied customers; faster awareness of important innovations and how they can be applied profitably; a stronger reputation within industry; improving the skills and general performance of the company workforce.

In this research a number of benchmarking criteria were considered to identify differences in performance levels and practices. For instance, generic benchmarking which investigates the strategy and practices of businesses, in order to understand and learn from their experience, functional benchmarking which compares between similar functions in different industrial sectors such as the manufacturing or the design process in Automotive, Aerospace, and Telecommunications. Competitor benchmarking which is a comparison between functions or performance and practices in similar industries. For instance, the current NPD strategy between company (A) in Aerospace and company (B) in the same sector.

Samples of the major findings of the benchmarking, particularly the benefits, the barriers and the methods adopted by companies practicing CE strategy are discussed in the following sections.

4.1 Steps taken for implementing CE

Due to the diversity of the industrial sectors involved in the study, in terms of product nature, size and major goals of each company, the steps taken to implement CE varied from one Company to another, as shown in figure (5). The common steps taken by companies towards implementing CE were functions co-location which was considered by 44% of the enterprises as the first step towards bringing GCE into action, while 52% of the companies had to re-organize the management structure of their company (ESPRIT 7752, D2.1 1994). These results match the findings of the UK Design Council Survey (1993), more than 50% of the organizations use product teams and co-located their team members in order to achieve better communications and decision making. IT tools were used by almost 30% of the companies to support CE, but it doesn't represent the strongest factor as some might expect. Training for all staff including senior managers and employees is a vital step, while 56% of the companies have highlighted the importance of this factor.

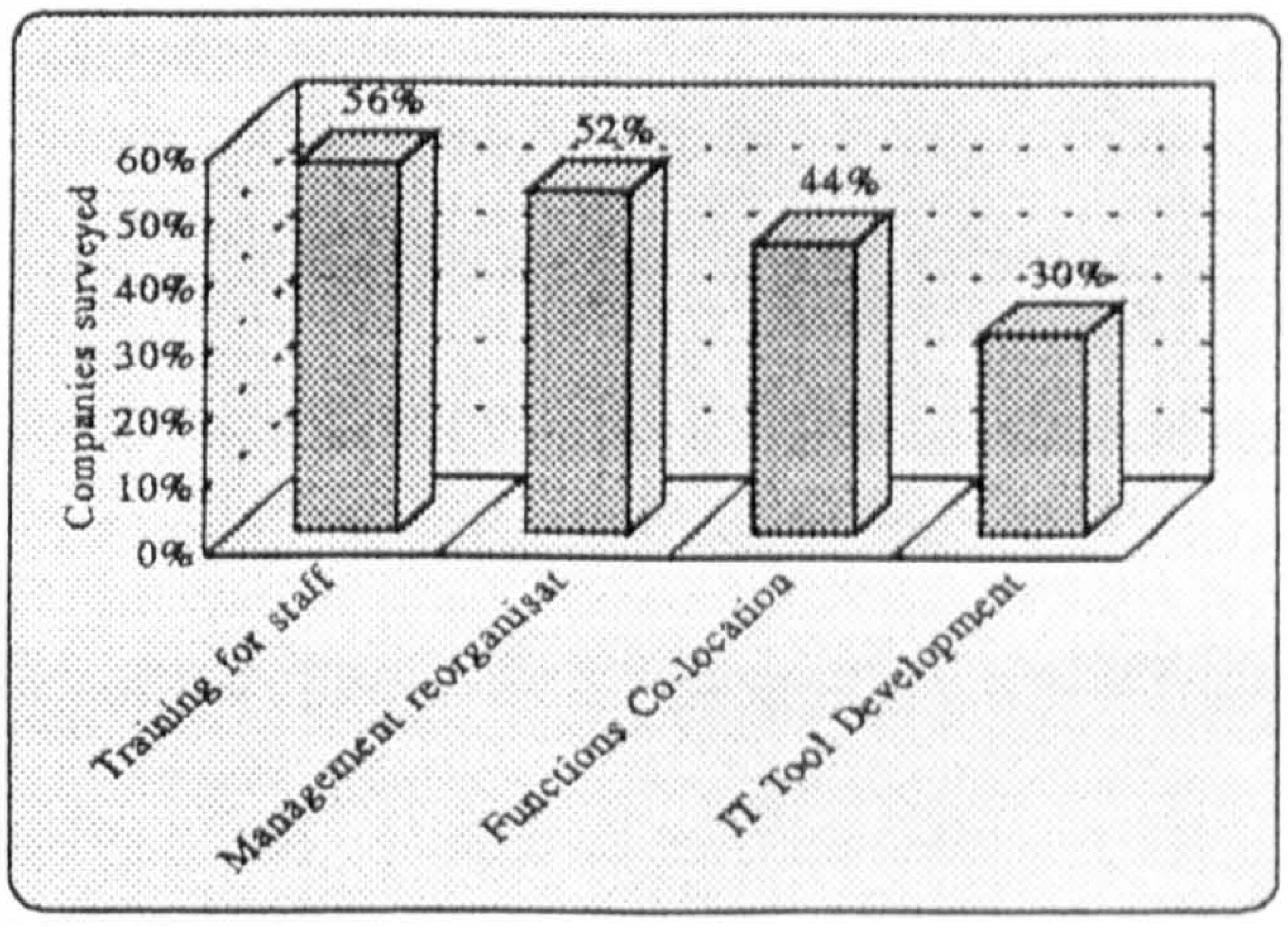

Fig (5) Steps taken for Implementing CE

4.2 Barriers to CE Implementation

The main barriers reported during adopting CE were management problems (41%) and resistance to change (41%) as indicated in figure (6). Lack of expertise or information was highlighted by 33% of the companies as major difficulties to persuade their people of the importance of adopting the CE concept. Similar outcomes were stressed in the UK Design Council's survey in 1993, 70% of the companies participated in that survey mentioned that lack of CE information and difficulty in knowing where to start as crucial barriers to CE implementation. The same study has also revealed that 60% of CE knowledge was gained through self-learning. These results and others emphasize the necessity for training and development for the management as well as for individuals to achieve a clear understanding of the philosophy.

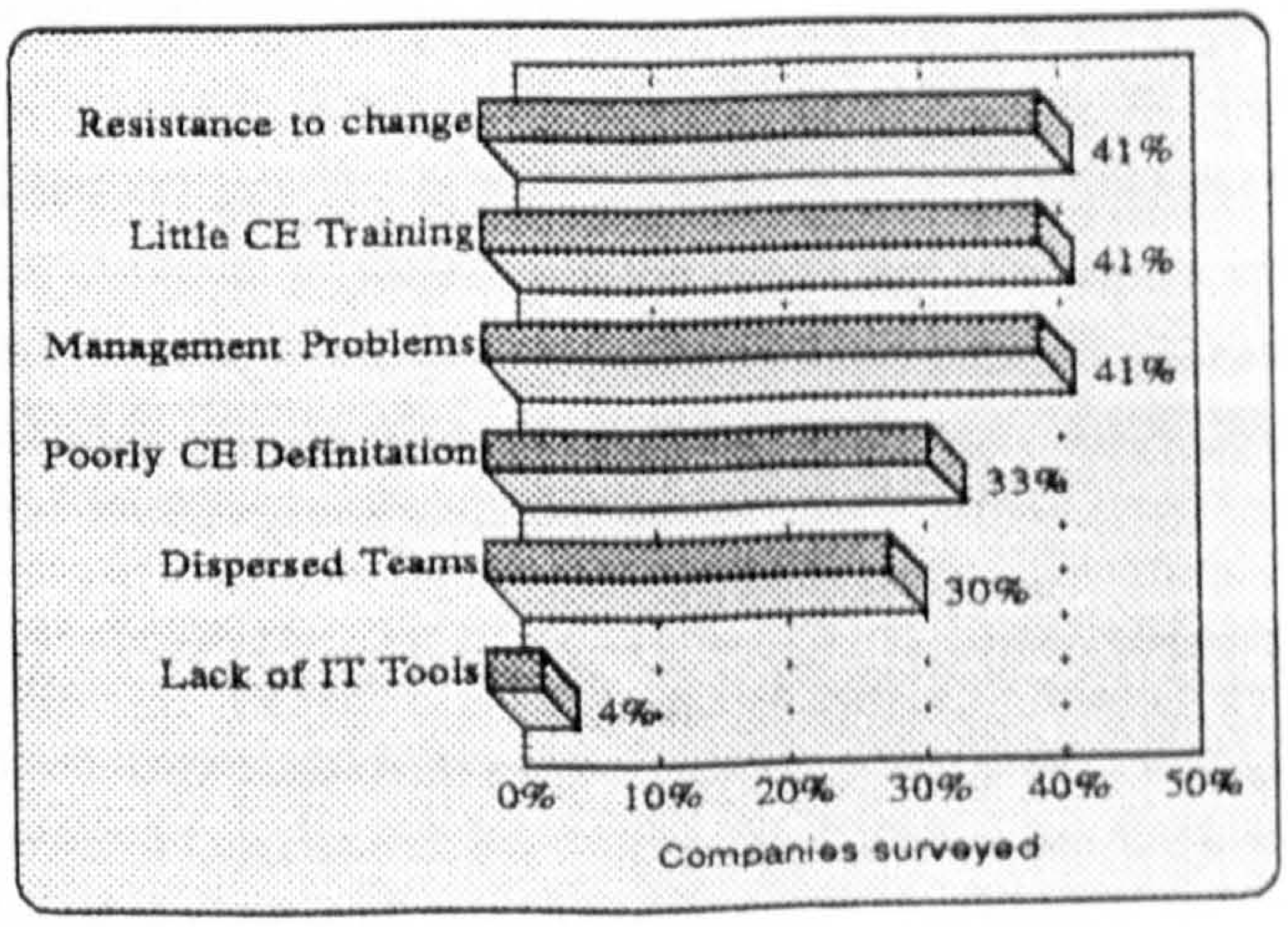

Fig (6) Problems Encountered during Implementing CE

Companies that have been practicing CE have focused on team building skills and the use of TQM, and quality function deployment (QFD), the techniques which entails the involvement of customers and suppliers as principal players or the key role to the business success. Surprisingly, lack of Information Technology tools was hardly mentioned as a barrier, only 4% of the companies reported IT as a problem they had to overcome for utilizing the CE approach. Some participants have pointed the need for integrating various IT tools such as CAD/CAM, expert systems, process planning systems, etc in order to facilitate the data sharing process.

4.3 Benefits of Concurrent Engineering Practice

Significant CE benefits were reported in the study as shown in figure (7), the most remarkable benefit was shorter time to market (70%). In addition to other benefits such as: improving the communications (59%); improved product quality (56%); reduced development costs and better management (33%); reduced design change (48%) which means shorter ramp-up time and improving the company's competitiveness. The Design Council Survey 1993 has also shown that late design changes can seriously affect development costs, as they are probably the most expensive to implement. It also showed that between 30% to 50% of the companies were suffering from the high level of engineering rework.. These benefits are very much interrelated and lead to other achievements such as increasing market share, and customer satisfaction.

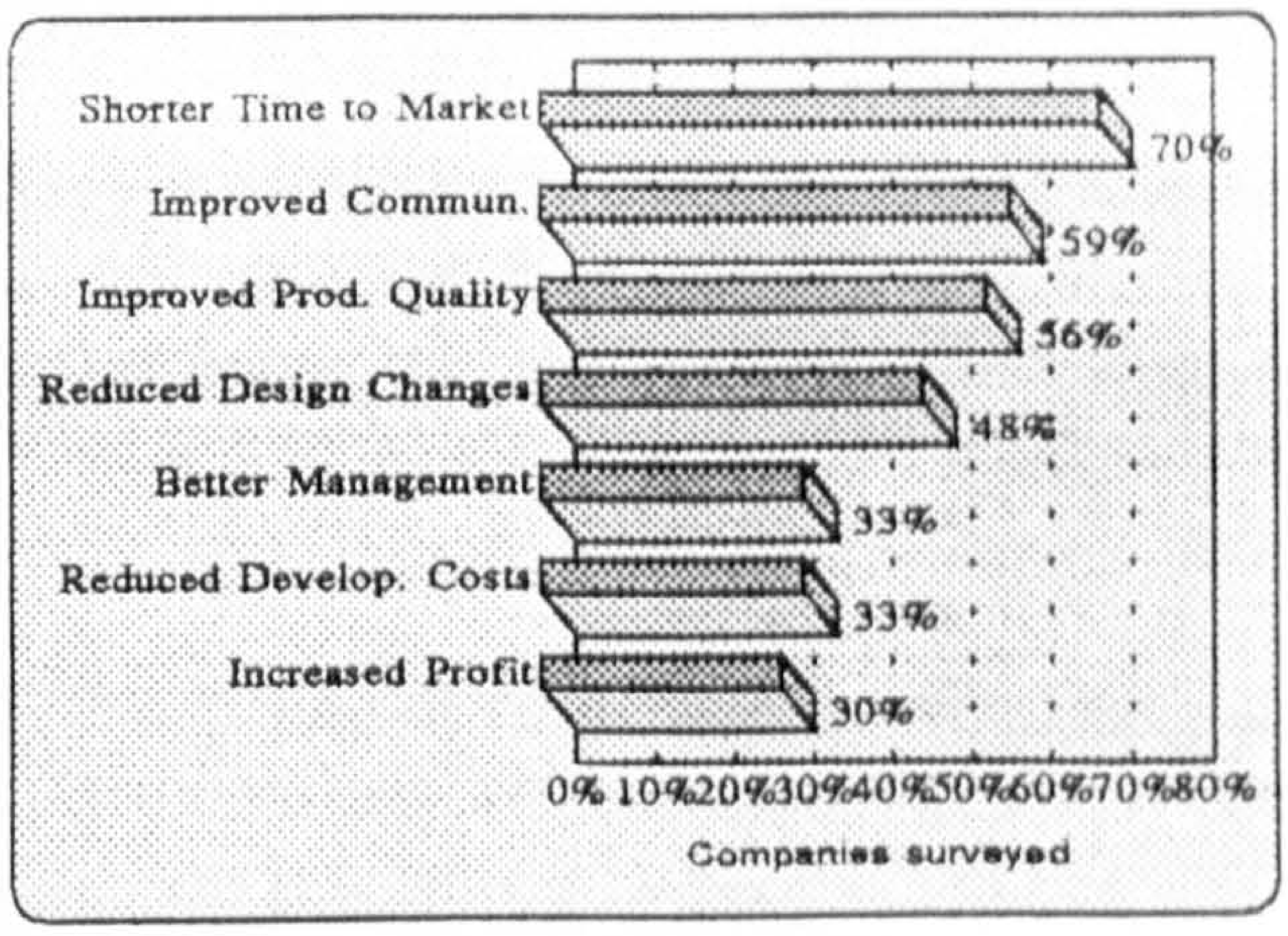

Fig (7) Benefits of using CE strategy

5. A Strategy for Global Concurrent Engineering (GCE)

Companies wishing to embark GCE need a logical analysis of what issues should be addressed, in what order and by what tools and techniques. They need a step-by-step approach to help them systematically improve operations and understand the impact of their decisions on other parts of the business. They need to highlight potential pitfalls, so they can understand, what might go wrong, why, and how it can be prevented. The conducted survey showed that over 50% of the participants identified cultural or communication issues, as major obstacles to progress in global market. Most companies experience in GCE are focused on learning how to break down barriers between departments. Companies should invest enough time on getting all aspects of the product, process, customer requirements and support sorted out as early as possible during the design stage. If they do, they will gain great benefits, such as fewer engineering changes, and faster and cheaper product development. The following points were drawn from the current study as substantial recommendations for creating a GCE environment within an organisation.

5.1 Commitment from senior management

Management commitment provides a conductive environment and senior managers should understand the philosophy of GCE and its benefits in order to be more dedicated. So they can encourage their employees for implementing the strategy and emphasis on the necessity for the change when it is necessary, to meet market requirements. As discussed earlier over 41% of the companies involved in the benchmarking admitted that management and resistance to change are critical problems that could be faced during utilising GCE strategy.

5.2 Employee Commitment

Employees have an image of their company which differentiates it fundamentally from others and makes it a unique and special place. Their commitments increase the effectiveness of team work and ensures successful implementation of the findings, and it can be built by employee participation. Emphasise on team-work, involving all employees at every level, based on a flattened management hierarchy is essential. Companies should challenge all current thoughts and beliefs relating to all aspects of the business operation and stress suggestion schemes which involve all employees contribution.

5.3 Clear Strategy

Organisation efforts and strategy should be clear and moving in a common direction towards on-going company wide progress. Visualise the company activities towards continuous process improvement. Develop not only a vision for the future but also the necessary steps towards achieving it.

5.4 Teamwork

An essential component of GCE is teamwork. The quality of collaboration within the teams, co-operation across different teams, operating units and divisions, are important factors for companies success. Taking a product from concept to production is achieved by people, the simplest method of getting everyone involved is to create a team at the concept design stage. For each new product, a team should be defined which includes representatives from all major stake holders; finance, marketing, design, manufacturing, simulation, testing, production planning, and quality, ie. representatives covering the entire product life cycle and its associated cost implications for the business. Those teams should share responsibility and each team should have a complete responsibility for the end product it delivers. Team members should also share responsibility for attaining the team's goals and objectives as well as the overall direction and achievement of the task. It is through team working that cross fertilisation occurs ensuring the success of the project. While team approaches appear to have been effective in a number of instances, some difficulties remain unsolved. First, group decision making, especially for creative tasks, can be difficult and the effective management of the team can be demanding (Harfmann, 1987). Second, the team members may not have detailed knowledge of all aspects of the life-cycle of the product and the design may therefore be biased towards particular considerations. Third, the cost of maintaining a team, and the difficulties of assembling the team, may make it uneconomic or onerous to use. This is specially true for small or medium volume products.

5.5 Team building skills

Organisations should invest and concentrate on team building skills through establishing well defined long term training schemes. Survey results have shown that lack of awareness of GCE approach is one of the major barriers towards implementing its philosophy. Several companies and organisation are encountering difficulties to persuade their people with the concept because of lack of information and poor definition of GCE. Team members should not experience culture shock as they begin work in an environment, where it is illegitimate to challenge working practices, procedures and corporate norms. People are the most valuable resource, therefore, it is important to provide them with better communication and clear guidance, as to what is expected from them whilst recognising the risks involved and the changes that are likely to occur. Consequently, the important issue to reduce risks is to plan accordingly, and to continuously strive to improve future performance.

5.6 Communication and Functions Co-location

Communication is vital to any change, it increases the efficiency of the change process. How the teams communicate is very important for making the right decision quickly during the product development session. Some of the organisations collocate their team members in order to achieve better communication, others use a combination of both face to face meetings, information systems to facilitate better communication, understanding, and making quicker decision at early stage during the product life-cycle.

5.7 Technology Enablers

Information Technology (IT) tools such as engineering database management systems (EDM) assist in getting information to the right people at the right time with minimum effort. An IT infrastructure is needed which can support the flow of information between the people involved in all aspects of the business. Members of the team need effective and efficient ways of transferring data/drawings and also communicating. The IT system employed should hold all information about the product and maintain the integrity of the data, integration of tools, techniques and teams can be co-ordinated through a paper based, or computer based formal project management system. One of the essential and basic principles of GCE is the concurrency of activities. This approach has contributed radically to productivity, cycle time reduction, quality, and shorter product development times (up to 33% shorter, Leppitt, 1993). The use of technology to enable this to occur is essential, technology facilitates easy access to information through either local area networks or wider area networks; eg materials information should be available through the company database or through more remote databases accessed via modem anywhere in the world.

5.8 Data sharing and standardisation

The use of the international standard for the exchange of a product model data (STEP and CALS) is important for facilitating data sharing. All teams should be able to get access and share data throughout the organisation very easily. The preliminary step towards facilitating data sharing is data integration, centralisation, network system, and data standard. Cross-functional communication and simultaneous tasking between design, development, production and marketing departments are necessary to reduce overall product development time and to design product which more closely matched customer requirements.

The survey shows that lack of product information (historical data), and information recording and retrieval in terms of job costing, cost of material, man power, processes, problems etc, for previous projects and products should be available in an easy access way at any time for the product developers. If this happened mistakes made in previously can be predicted and avoided, IT tools can be useful for that purpose. Analysing the information and decision consequences should be assessed and the impact should be pointed out.

6. An Architecture for Global Concurrent Engineering

One of the major principles of this project is to develop an architecture or description model on how to design a product within Global Concurrent Engineering environment. The proposed architecture is applicable to various types of industrial sectors. It is based on the CIM-OSA model and modern systems theory (Klittich, 1994). CIM-OSA model structured on three main dimensions: (i) the life-cycle dimension in terms of design, requirements, and implementation; (ii) the dimension concerned with the degree of particularization called the dimension of generality, which are divided into three levels, generic level, partial level, and particular level; (iii) The dimension of structure and behavior which named as the dimension of views. This dimension implies functional, informational, resources and organizational views. The input to all these components were mainly from the results of the data collected from the companies, which gives full insight about what companies are doing and needing. Further discussion of each dimension is presented below.

6.1 The life-cycle dimension of the CIM-OSA architecture has been expanded to include other five phases as follows:
Phase 1: problems analysis
Phase 2: construction and integration
Phase 3: detail design
Phase 4: control, maintenance and support
Phase 5: implementation and carrying through the operational system.

The above phases considered here are basically the analysis, design and construction of the global concurrent engineering system rather than the life-cycle of the product created in the global concurrent engineering system.

6.2 The dimension of views: the dimension of views encompasses a set of views, such as functional views and their interdependence, dynamic view including system behavior, an information view, a resource view, an organizational view, and cultural views. Then there are two new views have been added to CIM-OSA architecture, which are the differentiation of the original CIM-OSA views. For instance, in CIM-OSA the functional view includes a modeling of tasks and dynamic behaviour as one component. This has been differentiated in the developed architecture to emphasis the importance of each view.

6.3 Main components of the Architecture: the architecture consists of three major levels, each level including two sub-architectures, one procedural focuses on how things can be done, and the other on configurational and solution oriented to illustrate potential system solutions. Above all functional and dynamic views were considered in order to create a platform to the architecture. In addition to the culture view to supplement the organizational view in order to analyze the cultural factors of GCE. The model has also *a mode of inquiry* dimension which is applicable to various views and particularly the cultural, the organizational, and the resource view. Further details study is required to explain more about how the proposed architecture could be implemented with specific company's considerations.

7. Lessons Learnt from the International Collaboration

Working in an effective international collaboration provides a unique experience in improving global product management operations. There is no doubt that globalisation of manufacturing requires efficient transfer of manufacturing knowledge from various regions across the world. The test case participants have gained great experience as a result of the benchmarking exercise, through monitoring their company's performance against others in similar industrial sectors:-

- Discovering the pitfalls of their business and learning more effective management strategies. The GCE approach has contributed to major breakthroughs in productivity and quality gains in the manufacturing domain.
- The international collaboration itself was a crucial exercise in giving the consortium practical insight to how multidisciplanary teams could be managed, data sharing, standardization, and decisions conflict resolution.
- The feasibility study have addressed research areas which need to be investigated in order to fulfill the requirements for establishing a GCE system. It has also identified shortfalls and reasons why visionary objectives could not be achieved.
- Allocation of responsibility for the workload have to be clearly defined at the very begining of the project.

8. Conclusions

The research reported here was conducted by collaborators from various countries representing organisations and research institutions from varied backgrounds. A comprehensive benchmarking exercise was carried out and data was collected from different industrial sectors. As a result of the study a set of guide lines for GCE practice were extracted. Some of the results were also used to define specifications and requirements to establish a framework for a GCE architecture.

The study has shown that CE is a competitive strategy which aims to increase market share, customer satisfaction, and reduce product lead time. A key to CE is effective cross functional teams which integrate the development process using both organisational and information management methods. Effective teams requires a supportive managerial and organisational environment. The importance of managing teams and increasing responsibilities at teams level to convince people in advance with the benefits of the concept are substantial. An infrastructure for transferring technology together with the co-ordination of the product development processes are crucial elements for establishing concurrent engineering environment. An infrastructure would determine the degree to which data from customers, suppliers, and other business functions can be meaningfully organised and accessed by the development team members. This enables the team members to create a common understanding of the product and their related processes involved in its product introduction. This research area has shown its necessity and further study seems worthwhile.

Acknowledgements

This paper presents some of the major finding of a collaborative research carried out by Test Case 3 of the IMS Feasibility Study Consortium members. The programme is sponsored by the Commission of the European Community. The author acknowledge and appreciate the Commission's support and the contribution of all the consortium members.

List of Abbreviations

IMS	A Multi-national Collaborative Programme for Global Manufacturing.
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CALS	Computer Aided Acquisition and Logistics support
CIM-OSA	Open System Architecture for Computer Integrated Manufacturing
DFC	Design for Cost
DFMA	Design for Manufacture and Assembly
ECO	Engineering Change Order
GCE	Global Concurrent Engineering
EDI	Electronic Data Exchange
PDM	Product Data Management
FD	Quality Function Deployment
IT	Information Technology
STEP	Standard for Exchange of Product Model Data
TQM	Total Quality Management

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A METHODOLOGY FOR PRODUCT LIFE-CYCLE DEVELOPMENT FOR GLOBAL MANUFACTURING
(IMS-GCE, Test Case 3)

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Abstract

This paper demonstrates the framework and major objectives of the ESPRIT project 7752, IMS-GCE. The collaboration is international and the consortium members represent a cohesive group from the various regions, including companies and research institutions from the UK, USA, Canada, Italy, Denmark, and Finland. Those collaborators have been working effectively together on a comparative study of Global Concurrent Engineering to find the best practices and major constraints, and to design an architecture for a concurrent engineering system for global manufacturing. Some of the results which show how a product can be manufactured in several countries with ease of co-ordination that results in highly efficient production and logistics are discussed.

1. An Overview

Intelligent Manufacturing System (IMS) is a multi-national project and encompasses six test cases. The technical themes of the test cases are: global manufacturing, clean manufacturing, enterprise integration, system component technologies, human and organisational aspects, and advanced materials processing. Test case 3, Global Manufacturing, has a consortium which comprises partners form the UK (TransTec PLC, and De Montfort University Leicester), Italy (Synatx Factory Automation), Denmark (Odense Steel Shipyard and Technical University of Denmark), Finland (NOKIA and VTT), the USA (North Carolina State University and California Polytechnic State University), and Canada (Northern Telecom and Carleton University). This project investigates and illustrates methodologies for global development and manufacturing of products within a Concurrent Engineering (CE) environment, for organisations that operate on a global basis "world class". Globalization in this context implies that the product or different parts of the products can be manufactured in different alternative production sites around the world, according to substantial factors, including technology and resources availability. It also incorporates the nature and expectation of the product market.

The essence of concurrent engineering is not only the concurrency of the activities but also the co-operative effort from all the teams, which leads into improving company profitability and competitiveness. The measures for productivity are usually based on time to market, product cost, market share, and quality. In reality these factors are inter-related and CE philosophy is targeting a mix of all these factors that gives an overall framework or strategy to the company. For example, taking into account the design processes as early as possible during the product life-cycle development might expose alternative solutions that could provide remarkable quality improvement for a diminutive cost increase.

In this research the definition for CE stated by the US Institute for Defence Analysis (report R-338, 1988) has been adopted, "Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes including manufacturing and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements". This definition focuses on the parallelization of the processes during the design stage, but our research considers the globalization as well as the concurrency issues. Further description of the major goals of this project is presented in the following section.

2. Major Goals and Objectives

The major objective of this project is to demonstrate the improvement that can be made to global manufacturing capability through the implementation of concurrent engineering techniques which have been generated for, tried, tested and evaluated within companies operating in national and international markets. This project aims to design methods that can effectively support Concurrent Engineering for global manufacturing. It is believed that this approach can improve designs, reduce lead times, reduce costs and improve quality to help to ensure the future viability of manufacturing industries in the region. The project objectives are: (i) to establish the extent to which Concurrent Engineering is practised; (ii) to identify the critical constraints with respect to global manufacturing in terms of technology, technology management and human resources; (iii) synthesise the best practices of Concurrent Engineering and to diminish the effects of the critical constraints; (iv) to design an architecture of a Concurrent Engineering System for global manufacturing, which represents a model of the functional activities; and (v) to disseminate the results through a Global Concurrent Engineering workshop.

3. The IMS-GCE Project Structure

The project work program is undertaken through five work packages; four of the work packages are directly related to the stated objectives and the fifth work package is the project management, which controls and co-ordinates the total project, as shown in figure (1).

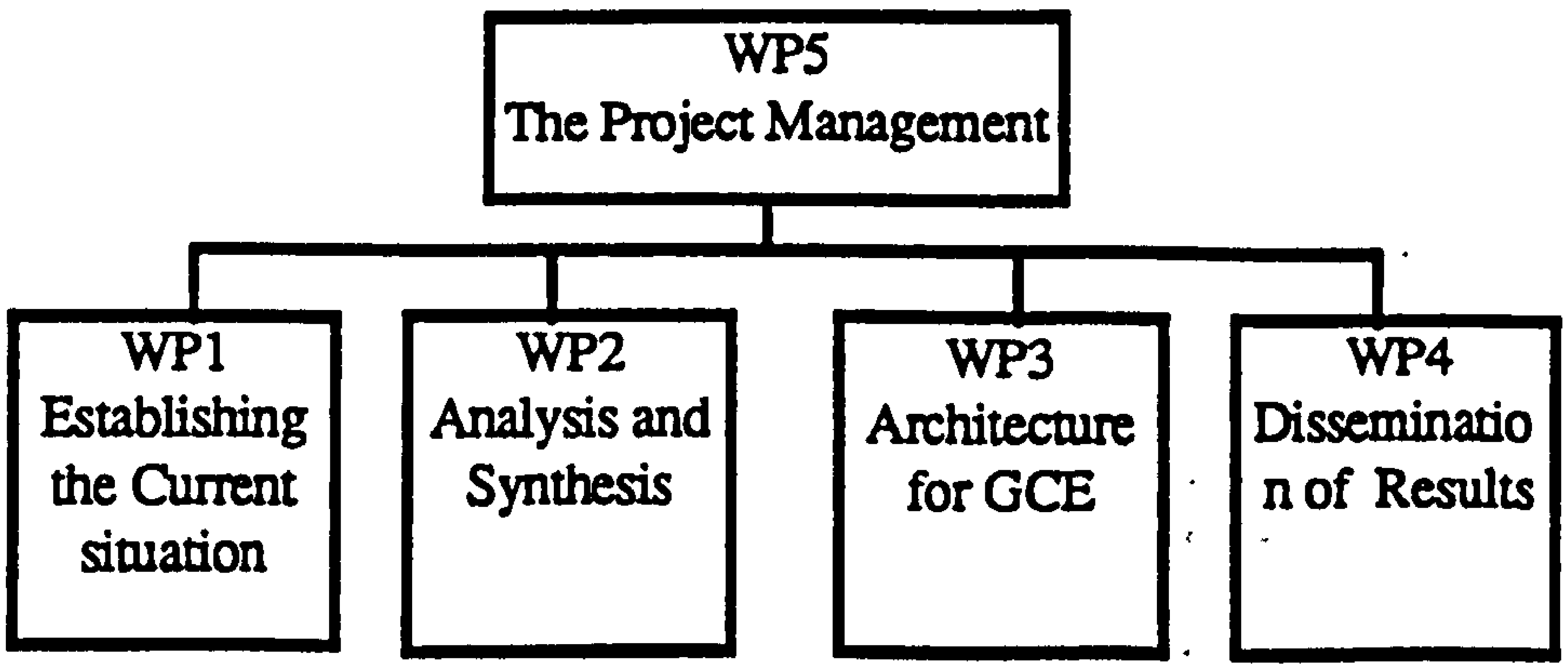

Figure 1: The IMS-GCE Project Structure

4. Research Methodology

A world wide survey was carried out in order to provide the information needed for defining the best CE practice and to build the GCE architecture. Figure (2) shows the research methodology implemented in this study. Over 320 companies were identified, but only 150 distinguished organisations and companies were approached as suitable candidates to participate in the GCE survey. The selection of those companies was based on two major factors, first these companies practise concurrent engineering strategy and secondly, these companies are actively manufacturing and marketing in a number of countries. After the identification of the companies, tools for investigating the practices of these companies were developed. One of those tools is a questionnaire used for collecting the data needed for the research. The questionnaires were designed to address a wide range of issues to establish how GCE is exercised in various organisations. Those issues are technical, management, and psychological issues. They are also designed in such a way to allow examination of different factors for NPD projects. To ensure that suitable feedback is achieved finite, logical and quantitative types of questions were included in the questionnaires.

The corporate level is addressed by a questionnaire developed and managed to examine corporate policies, strategies and practices in the implementation of GCE and the organisation of product development in the company. The second level of analysis examines the relationships between management and project teams. This level of analysis focuses on factors determining the effectiveness of GCE practices at the development program and project level. It surveys project team leaders, design and manufacturing team members, and managers working directly with project teams. The third level of analysis, the Infra-project level, examines the internal operation of the teams. These issues are focusing on the R&D Design, manufacturing interaction on the teams and their locations. It also examines the team's satisfaction issues.

The strength of the IMS-GCE research concept is that it allows for the linkage of these three levels of analysis within each company. Corporate or business unit strategies and policies can be linked directly to project team decisions and processes, which can be directly linked to summary and individual measures of team satisfaction, cohesion, and commitment. This design is based on a Global Concurrent Engineering approach which is multi-level and comprehensive. It allows for the hypotheses concerning the relative merit of different CE strategies and policies in influencing the outcomes of specific development projects, both in terms of meeting business goals and in terms of worker and management satisfaction with the development process.

5. Benchmarking Strategy

The essence of benchmarking is based on competitive performance according to other external perspectives. It is no longer limited only to comparison with competitors, but also aims to gain competitive advantage. It is the process of comparing business practices and performance levels between companies in order to gain new insights and to identify opportunities for making improvements. The greatest benefit is likely to be achieved by focusing on those areas of the business that are critical in driving competitive success. Emphasis is placed on understanding the processes that deliver performance and best practices in relation to those processes. Benchmarking helps to set strategy and identify new techniques. It also maintains the stimulus for continuous improvement. The key for best benchmarking practice should emphasise on understanding the actual performance of the business rather than just comparing results.

The collected data was analysed to identify differences in performance levels and practices according to the following benchmarking criteria: functional benchmarking, competitor benchmarking, and generic benchmarking which investigates the strategy and practices of businesses, in order to understand and learn from their experience. This research concentrates on generic benchmarking because of its importance.

5.1 The main Findings of the Benchmarking

In this paper samples of the benchmarking results are presented, particularly the benefits, and the barriers of implementing CE, in addition to the major steps and methods which are adopted by companies practising CE strategy.

5.1.1 Steps taken for implementing CE

Due to the diversity of the industrial sectors involved in the survey, in terms of product nature, size of the company, major goals of each company, the steps taken to implement CE varied from one Company to another. Figure (3) shows the various common steps taken by the companies towards implementing CE. Functions co-location was considered by 44% of the enterprises as the first step, while 52% of the companies had to reorganise the management structure of their company to utilise CE. These results match the findings of the UK Design Council Survey (1993)[4]; more than 50% of the organisations use product teams and co-located their team members in order to achieve better communication and decision making. IT tools were used by almost 30% of the companies to support CE, but it doesn't represent the strongest factor as some might expect. It is interesting to see that 56% of the companies emphasise the importance of training for staff as a substantial step for good CE practice.

5.1.2 Barriers to CE Implementation

The major barriers reported during the changes to CE were management problems (41%) and resistance to change (41%), figure (4). Poor definition and lack of expertise or information were highlighted by 33% of the companies as major difficulties to persuade their people of the concept. Similar outcomes were stressed in the UK Design Council's survey in 1993, 70% of the companies participated in that survey mentioned lack of CE information and difficulty in knowing where to start as crucial barriers to CE implementation. The same survey has also revealed that 60% of CE knowledge was gained through self-learning. These results and others emphasise the necessity for training and development for the management as well as for individuals to achieve a clear understanding of the philosophy.

In the survey 41% of the companies indicated that lack of training was a major obstacle. On the other hand, companies which have been practising CE have focused on team building skills and the use of TQM, and quality function deployment (QFD), the techniques which entail the involvement of customers and suppliers as principal players or the key role to the business success. However, lack of Information Technology tools was hardly mentioned as a barrier; only 4% of the companies reported IT as a problem they have to overcome for CE implementation, which means that CE requires changes in the organisational issues rather than the technical one.

5.1.3 Benefits of CE

Significant CE benefits were reported in the questionnaire as shown in figure 5, the most remarkable benefit reported was shorter time to market (70%). In addition to other benefits such as:

- improving the communications (59%)
- improved product quality (56%)
- reduced development costs and better management (33%)
- reduced design change (48%) which means shorter ramp-up time and improving the company's competitiveness. The Design Council Survey 1993 has also shown that late design changes can seriously affect development costs, as they are probably the most expensive to implement. It also showed that between 30% to 50% of the companies were suffering from the high level of engineering rework
- CE also increased the profit of 30% of the companies.

The above benefits are very much interrelated and lead to other achievements such as increasing marketshare and customer satisfaction.

6. An Architecture for GCE

One of the major principles of this project is to develop an architecture or description model on how to design a product within Global Concurrent Engineering environment. The proposed architecture is applicable to various types of industrial sectors. It is based on the CIM-OSA model[5] and modern systems theory. The CIM-OSA model is structured on three main dimensions: (i) the life-cycle dimension in terms of design, requirements, and implementation; (ii) the dimension concerned with the degree of particularisation called the dimension of generality, which is divided into three levels, generic level, partial level, and particular level; (iii) the dimension of structure and behaviour which is named as the dimension of views. This dimension implies functional, informational, resources and organisational views. The input to all these components was mainly from the results of the data collected from the companies, which gives full insight about what companies are doing and need.

The life-cycle dimension of the CIM-OSA architecture has been expanded to include other five phases as follows:

Phase 1: problems analysis and detail design
Phase 2: construction and integration
Phase 3: preliminary and detail design
Phase 4: control, maintenance and support
Phase 5: implementation and carrying through the operational system.

The above phases considered here are basically the analysis, design and construction of the global concurrent engineering system rather than the life-cycle of the product created in the global concurrent engineering system.

The dimension of views: the dimension of views encompasses a set of views, such as functional views and their interdependence, dynamic view including system behaviour, an information view, a resource view, an organisational view, and cultural views. Then CIM-OSA architecture has been enhanced to include the cultural view in order to adequately describe the GCE application. Also in the CIM-OSA model the functional view includes a modelling of tasks and dynamic behaviour as one component. The proposed architecture deals with these views separately to emphasise the importance of each view.

Main components of the Architecture: the architecture consists of three major levels, each level including two sub-architectures; one procedural focuses on how things can be done, and the other on configurational and solution oriented to illustrate potential system solutions. Above all functional, dynamic and cultural views were considered in order to create a platform to the architecture. The model has also *a mode of inquiry* dimension which is applicable to various views and particularly the cultural, the organisational, and the resource view. Further detailed study is required to explain more about how the proposed architecture could be implemented with specific company's considerations. For further detail refer to ESPRIT Project 7752, Deliverable 3.2.

7. Conclusions

This paper has illustrated an architecture for GCE strategy. The proposed model is based on CIM-OSA framework considering other factors, such as cultural, organisational and the resource views. The model gives opportunity to designers to minimise errors, increase market share and customer satisfaction, reduce the product life-cycle time and cost during the design stage. It offers guidelines extracted from current practices for global manufacturing. It also highlights the importance for fast development of exchange manufacturing information and manufacturing technologies systems for industry throughout the world. The major findings of a world wide benchmarking survey amongst the companies implementing CE strategy were reported.

Acknowledgement

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List of Abbreviations

GM Global Manufacturing
GCE Global Concurrent Engineering

IMS Intelligent Manufacturing System
NPD New product development
TQM Total Quality Management
QFD Quality Function Deployment

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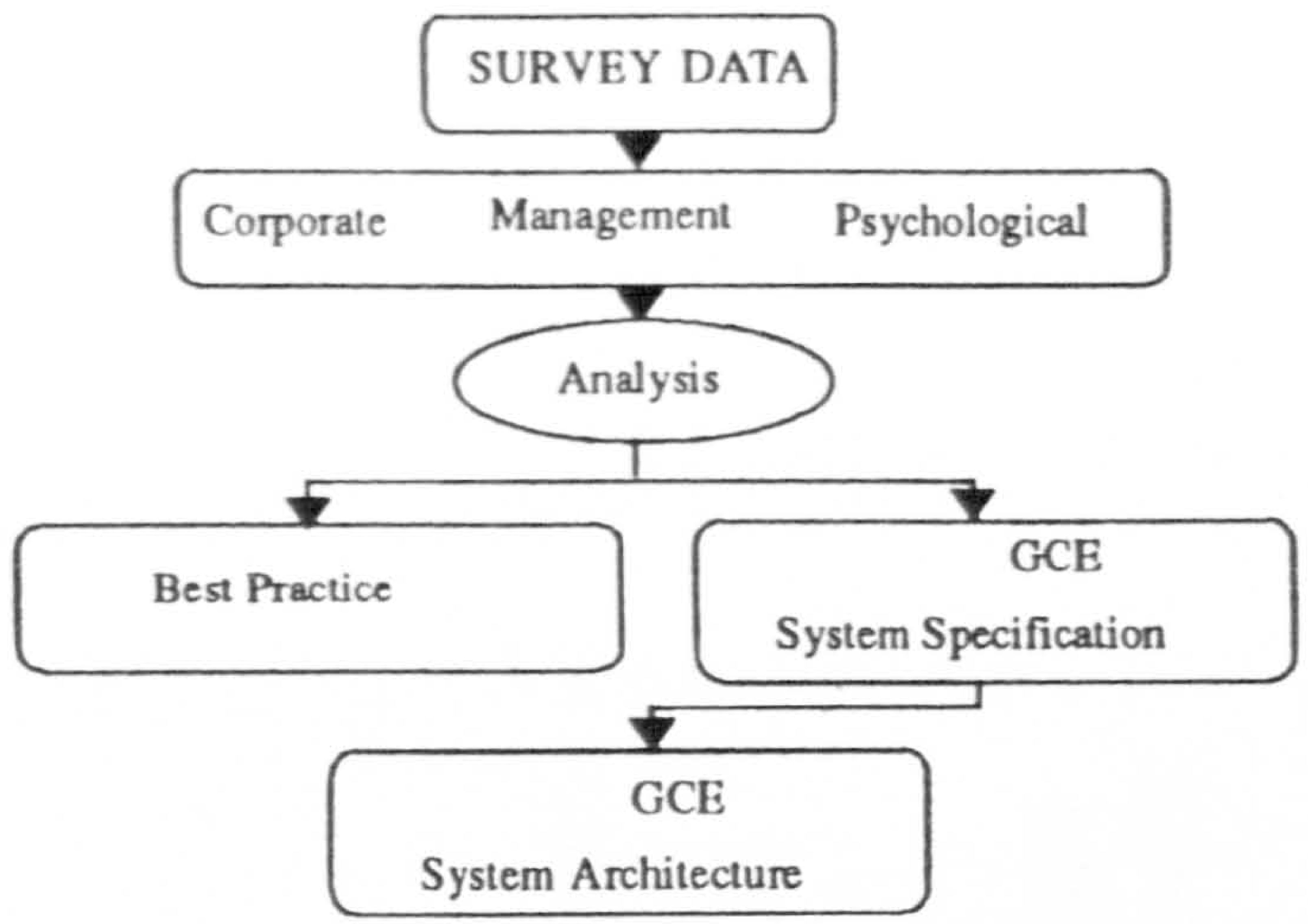

Figure (2) Research Methodology

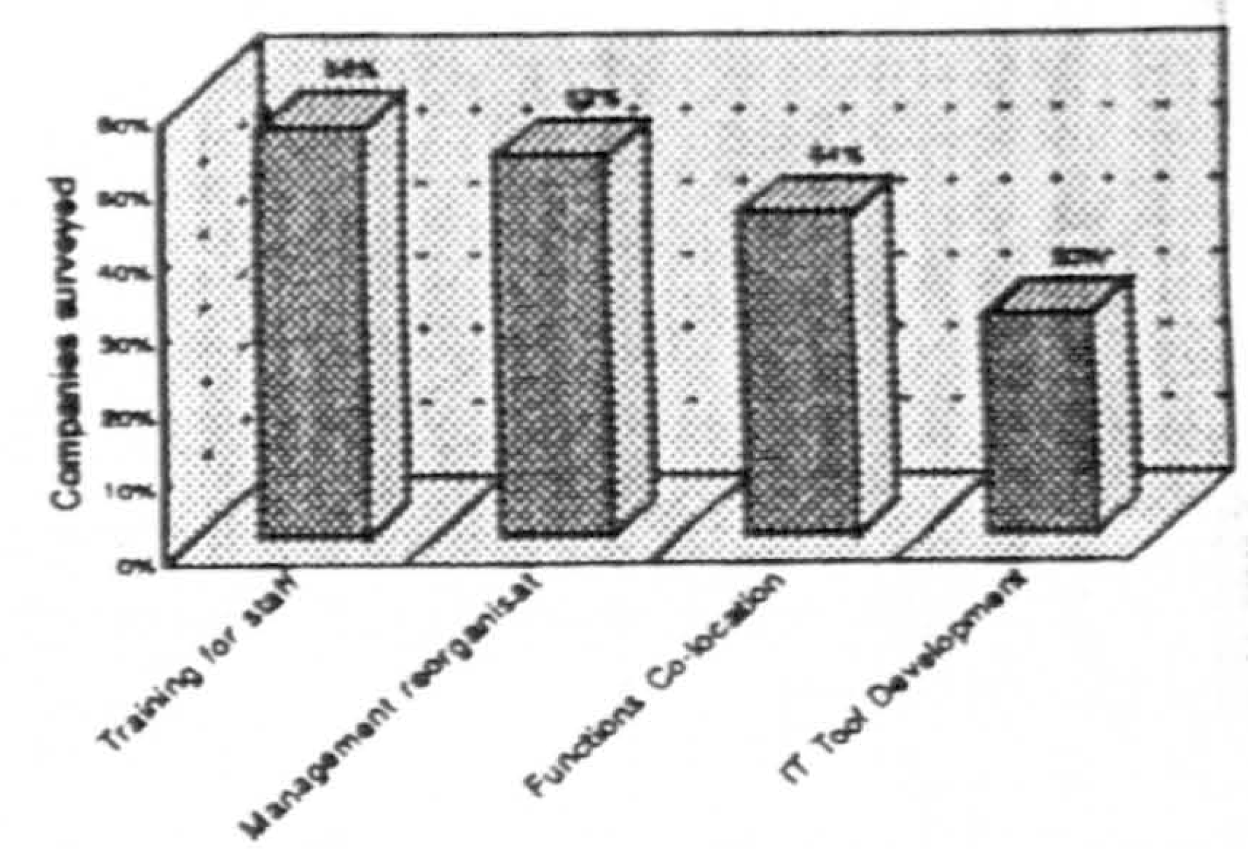

Fig (3) Steps taken for Implementing CE

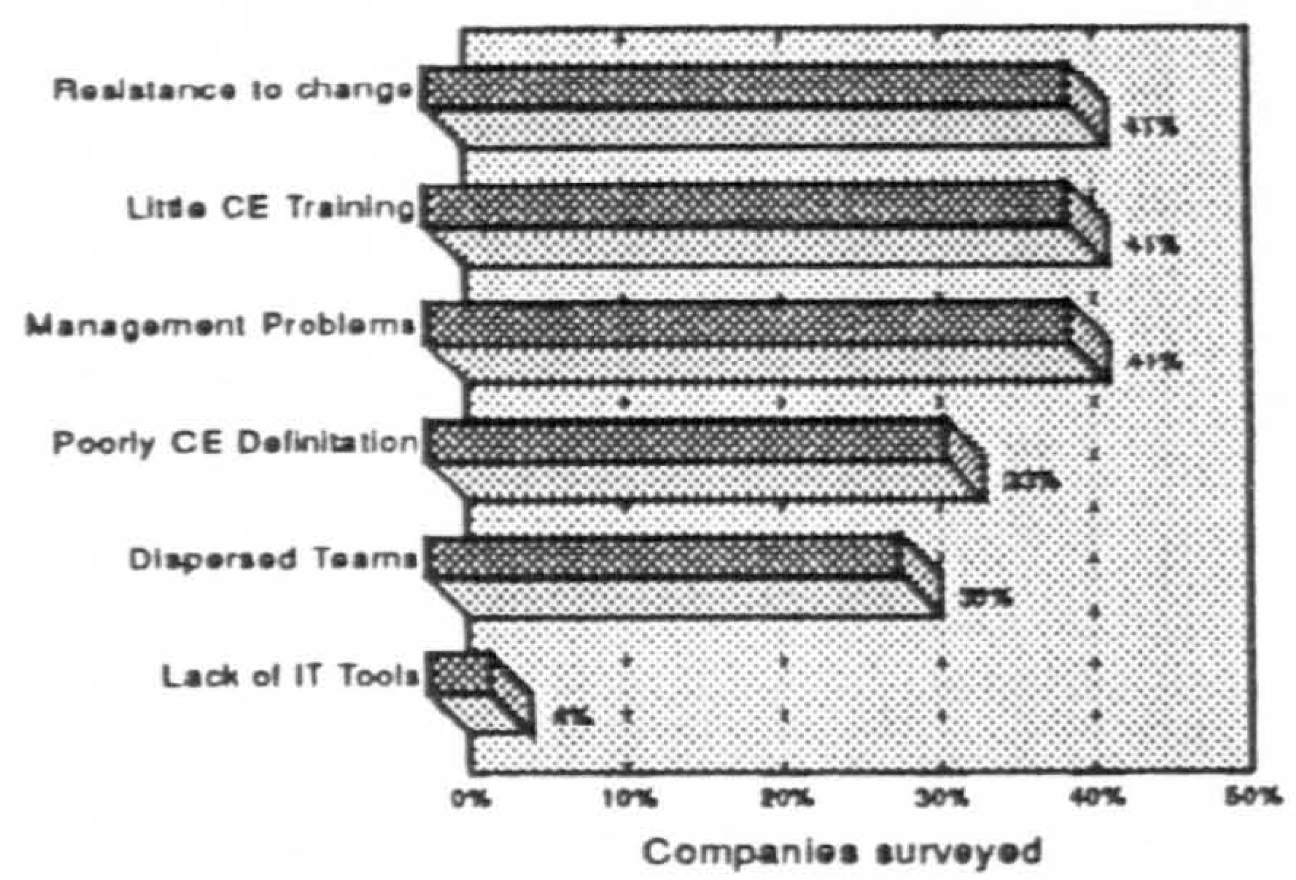

Fig (4) Problems Encountered during Implementing CE

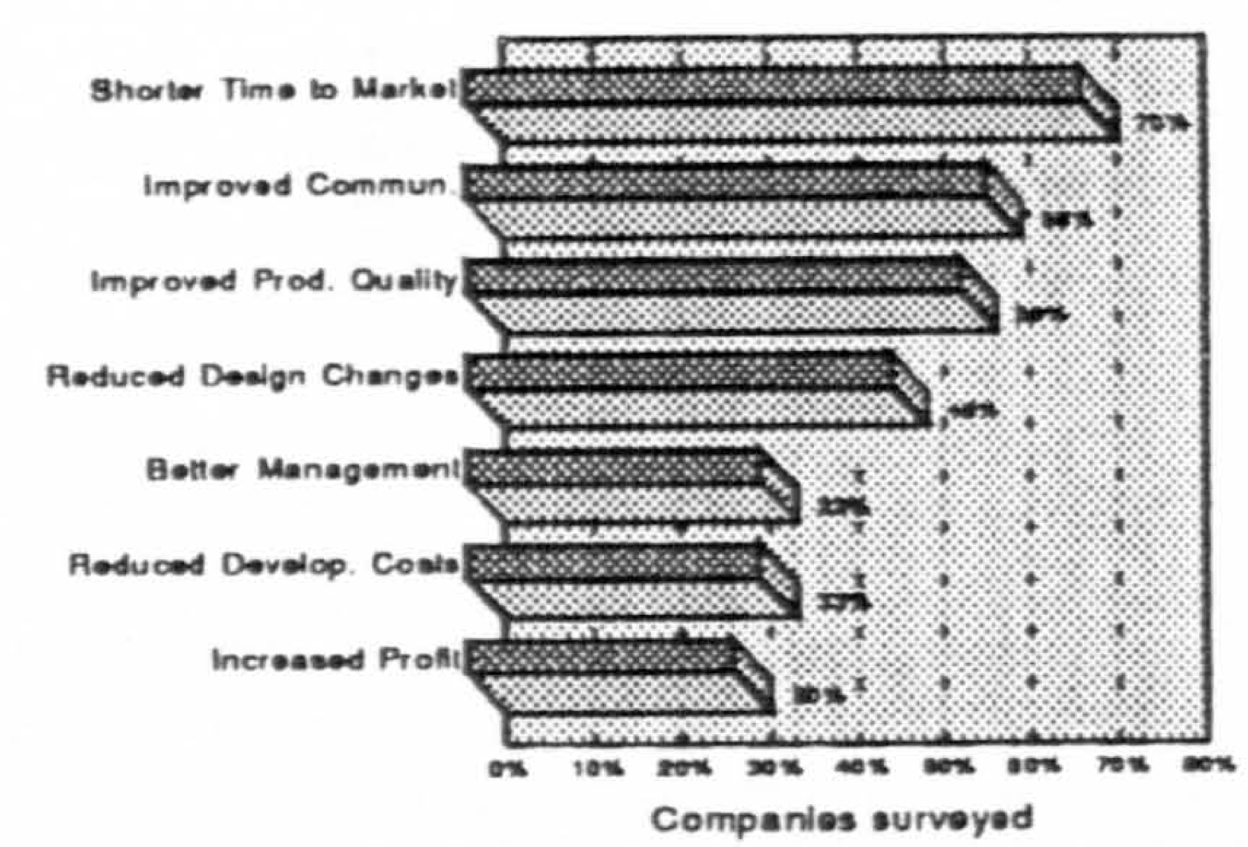

Fig (5) Benefits of using CE strategy

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AN INTEGRATED KNOWLEDGE-BASED AND CAD SYSTEM FOR FACILITATING THE IMPLEMENTATION OF CONCURRENT ENGINEERING

H S Abdalla and JAG Knight

Abstract. A design environment for supporting the product life-cycle development process through concurrent engineering technique is presented. The proposed technique is based on concurrent engineering principles and practices, it integrates and expedites the design, development and manufacturing process. The principle features of this system are the potential for time saving during the product development cycle, while assuring that the designed part can be manufactured in house with the available manufacturing facilities at minimal cost. Design possibilities and constraints are monitored from conception through to detail design; the knowledge-based system includes constraint rules about design functionality and manufacturing processes. The complete system enables designers to improve the manufacturing process, reduce production costs and significantly improve the quality of the product. This work was in response to the need for developing a CE system which could handle a wide variety of integrated information in order to assist designers in designing world class products.

Keywords: Concurrent Engineering, CAD/CAM, Feature Recognition, Knowledge-representation, Knowledge-based System, Design Constraint, Decision Support.

Introduction. The complexity of the requirements for today's global product in the world market place increases the pressure on companies to implement effective and efficient methods for developing, designing, manufacturing, and marketing the product, in terms of greater quality, reduced cost, and greater customer satisfaction. These factors are pertinent to decisions made during the design stage, which is considered as the most critical stage in the product life-cycle. Research has shown that upwards of 70% of a product's manufacturing cost is dictated by decisions made during the product design stage (Young, et al 1992). Decision made at this important stage has significant impact on final product cost and time to market. Concurrent Engineering (CE) has been shown to be a successful way of achieving the goal "get it right first time". It is a customer driven strategy which encompasses a combination of philosophies, and tools aimed at improving the product development process. There are "spin-off" benefits which can be gained as a result of implementing CE strategy, such as increasing market share, reducing product life-cycle development, shorter lead time, expanding the product range, and improving the quality of both new and existing products.

CE philosophy utilizes a cross-functional team approach to get the pertinent players involved in each stage of the product development cycle. Therefore, parallelisation of various activities, data standardisation, and integration of the product development process are critical criteria in implementing CE. Some of the principal requirements for implementing concurrent engineering strategy have been discussed by Parasad, et al 1993. Their approach highlights the possibility of collaborating designers to proceed independently, correlate interdependency, use existing information (data, knowledge, and processes), in addition to negotiating conflicts arising from design inconsistencies. Their work raised a series of research issues which need to be addressed to affect the practice of CE. Working relationships between people was identified as one of the main imperatives for implementing CE. Extensive training in team building, leadership, and the CE plan prior to actual start were some of the lessons learned from the implementation of CE at OECO Corporation, USA (Monroy, 1992). Benefits reported were significant, an overall lead time reduction by 50%, reduction in engineering changes by 40%, reduced unit costs, and general improvement in the product quality and reliability. Burhanuddin and Randhawa, 1992, have described a system that integrates product design specifications with material and process databases, and a simulation based analysis module. Their system allows product designs to be evaluated economically and technically, and to identify the best production environment. Sutherland et al 1988, proposed a methodology for a CE strategy which incorporates machining process modelling and the design of experiments to find robust product/process design in terms of a set of factors such as part material and machining conditions. It can be noticed that little attention has been paid in previous research work towards developing a system which provides a generic support and cost estimates to designers at an early stage of the product life-cycle development. In this research a concurrent engineering design environment has been developed for facilitating parallel execution of some of the engineering activities.

A design environment for supporting CE. There are few proprietary software systems which purport to offer a CE environment. However, in many cases, such systems offer a more efficient serial development but do not cross fertilise between differing aspects of the design process. The impetus at De Montfort University (DMU) has been to develop systems which underpin CE and enable parallel activities to function efficiently. The research initiative has been launched to establish techniques for achieving the following object:- (i) automated feature recognition from a solid modeller, (ii) first-order cost estimates for product design early in the design process, (iii) providing feedback about manufacturability concerns such as process limits or design inconsistencies. The DMU system consists of a CAD solid modeller and reasoning system; the development of the link between the two components was imperative to accomplish the contemplated approach. However, in general development of this sort of systems is not a trivial task, it inherent difficulties have to be overcome to affect a full system developement and implementation. A major problem encountered during developing the system was that most solid modellers available today represent part geometry in terms of low-level geometric and topological entities such as faces, loops, edges, surfaces, curves and points. These modellers do not provide high level abstractions of the part that relate directly to certain design functionalities or manufacturing characteristics. Such systems create significant difficulties and ,in general, cannot be used directly to derive applications such as machining cost estimation, and process planning. This work discusses an approach that is capable of overcoming most of these deficiencies.

An extension to the solid modelling system (Pro/Engineer)[7] programming interface has been developed using its Pro/Develop module to cooperatively assist designers in creating new applications. These applications can be directly integrated into the CAD System (Pro/Engineer) environment and to extract the necessary topological and geometrical information from the solid modeller during the design stage. Pro/Develop, the programmatic interface of the Pro/Engineer database, together with bespoke software written for the UNIX environment, have been used to access the database of the CAD System. Interface menus have been created to enable users to interact with the system easily and efficiently. This interface includes facilities to create features such as holes, fillets, and drafts. The further difficulty was to integrat the enhanced CAD system with a knowledge-based system (KBS) tool kit. The Knowledge Based System tool (KEE)[4] was chosen as an appropriate tool for building the KBS on A Sparc station (SUN4) was used as the development plateform. KEE supports frame-based objected-oriented programming and rule based reasoning. Each object in KEE is represented as a single frame, called a unit, and each unit is composed of slots. Each slot can contain data or a procedure which describes the characteristics and behaviour of the particular object.

The integration of the Knowledge Based System (KEE) and the CAD system was carried out as follows; KEE itself does not provide an external communication capability but allows complete access to Lucid's Common Lisp language. Common Lisp in turn supports a foreign language interface to communicate with PASCAL, FORTRAN, and C languages. These external languages can then open, read, and write files. On the other hand, Pro/Engineer can communicate to the outside world through the programmatic interface Pro/Develop. In a typical scenario, when a request for a geometric data query is received, KEE will invoke the proper Lisp method which calls a C routine with a command string as an argument. The C routine then puts the command string in a file and goes into a wait and check cycle until complete information comes back from the CAD system. When the C routine receives all the data requested back from the CAD system, another Lisp program is already loaded, and starts immediately to send the data back to the KBS.

System Operation. Once the user clicks on the UDF-Features (user-defined feature interface) Menu button, the Pro/Engineer system forwards geometric construction data and feature descriptions through to KEE. In addition, feature embellishments are carried out as the data transfer takes place. KEE then acts on the received data and creates corresponding data structures to store the information for further reasoning, analysis and applications. These are normally represented in an object-oriented form, consisting of geometric features and associated physical details. An analysis is then carried out which converts the physical features to a manufacturing feature structure.

The complete system enables engineers to improve the quality and reduce the cost of the product. It has also the facility to examine whether the designed part can be manufactured in existing manufacturing facilities and provides feedback to designers related to machining concerns that may arise. Moreover, it shows a if a particular context is incorrect, for example if the dimensions of a part are greater than the largest dimension that can be manufactured in the facility assigned to it.

An example of a feature recognition. Full identification of the part features during the design stage have to be available inside the KBS in order to proceed with other applications. The implemented knowledge-based system toolkit (KEE) supports frame-based-objected-oriented programming and rule-based reasoning. Its rules consist of a series of necessary and sufficient conditions. These rules have been implemented to identify a set of features topologically in terms of their shapes, and geometrically in terms of dimensions. For instance, when the conditions of a rule are satisfied, then the conditions are valid. So to recognise the type of a form feature such as a hole, the following approach was followed;
If < X > Then < Y > ; while X is the conditions and Y is the conclusions. For example, the recognition of a hole can be defined through the following rules:

If
(There is a circular top edge) and
(There is a circular bottom edge) and
(There is a cylindrical face) and
(There is a top face) and
(There is a bottom face)
Then
(The feature is a hole)

Similar procedures using these recursive rules were implemented to recognise feature type (holes, drafts, rounds, and slots) by matching the data of available feature's with predefined feature characteristics. After defining all the features, geometrical and topological, the system records and represents them in groups according to their types.

Knowledge-based Constraints. Design inconsistency is a major problem facing designers, especially when they consider downstream and topstream activities at the same time. One approach to this problem is use of a knowledge-based constraint system that contains a wide variety of information about design, process, and manufacturing rules. Such a system should be able to provide advice to designers during the product life cycle development stage. Bowen and Bahler, 1993, have investigated the possibility of a concurrent engineering oriented language based on the concept of constraint networks. These constraints have the capability of restricting the values that can be assumed by a group of one or more parameters. A knowledge based computer environment that supports CE by integrating and providing active assistance for various engineering activities, such as conceptual design and redesign, specification acquisition, and qualitative simulation has been described by Tong and Gomory, 1993. This system has a database which maintains the consistency of the design constraints. In this research a more practical knowledge-based constrained system was developed to select the appropriate machining process according to predefined constraints. A number of constraints about the existing manufacturing facilities and expertise are fomulated using KEE rules. These constraints are implemented to bound the machining processes and to show the feasibility of the part during the design stage and before making the final prototype. In this context manufacturing criteria have been utilised as rules to approve constraints. Using the manufacturing rules, the designer is able to examine whether the designed part can be manufactured with the available manufacturing facilities or not. For instance, if the designer specifies a hole with a specific diameter (d_h) the system will compare this diameter with the predefined diameter range "$D_{min} < d_h < D_{max}$". Warning is given in the case of inconsistency or invalid dimensions (hole diameter too big or too small). Consequently, the designer can select other appropriate dimensions. This can take place at a very early stage during designing the product; implementation of this strategy avoids manufacturing surprises.

An example for selecting the appropriate operation required to make a particular feature according to the predefined rules or constraints is shown below:

If

(The Feature is a hole) and
(The Diameter of the Hole D_h >= 1 mm) and
(The Depth of the hole <= 200 mm) and
(The Tolerance of the Hole < 0.01mm) and
(Additional Rules)

Then

(STEM Drilling is selected); STEM (Shaped Tube Electrolytic Machining)

Machining cost estimation. A system has been developed by Abdalla and Knight,1993 which includes an interface to enable users to interact with the system regarding machining cost estimation during the design session. The interface has been carried out using the KEE function facilities and designed to enable users to obtain information about not only the total cost but also the individual cost elements such as turning, milling, drilling or reaming, tapping, centre drilling and setup cost. If the cost of the product exceeds the targeted cost, then the system may suggest discontinuing the further development or redesigning the product. The system is developed in such a way that it collects data from various engineering activities in a CE environment and evaluates the design based upon the predicted costs of machining, assembly, material, testing, overhead and other drivers. This cost estimating system is different from the conventional product cost estimating systems, because the traditional cost estimating systems are not structured adequately to support CE.

Conclusion. A CE design environment system to address the issue of lowest cost design strategy of a part by concurrently taking into consideration different product life-cycle concerns during the product development stage has been presented. The system consists of an integrated KBS and CAD system which facilitates simultaneous consideration of various activities such as analysis and refinement of product and process data. The System gives a predictable machining cost estimation and continuous feedback to designers about possible manufacturing issues or requirements as the design proceeds. This approach is a fruitful way of showing the design feasibility as well as reducing the timescale and cost of the product design.

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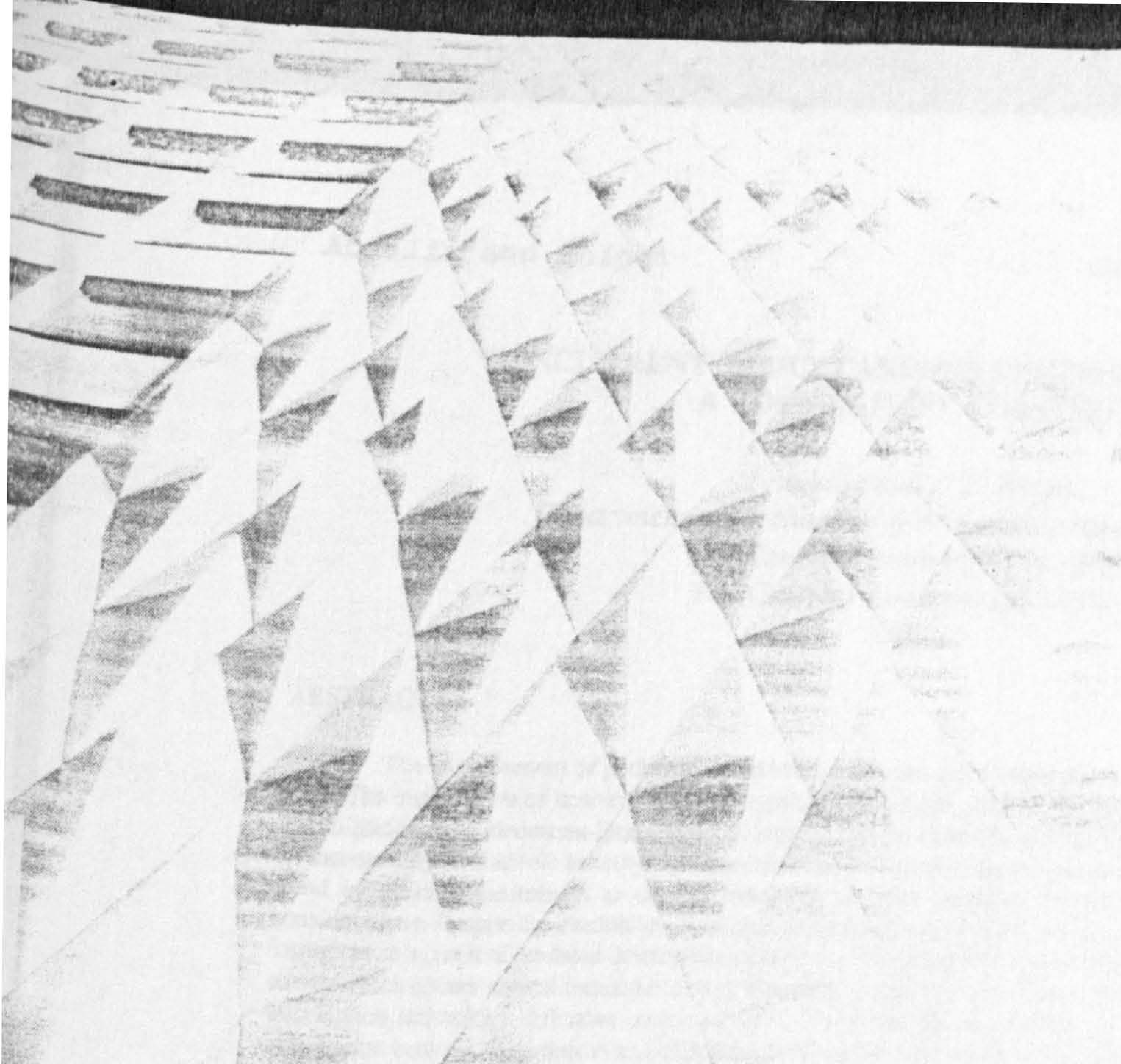

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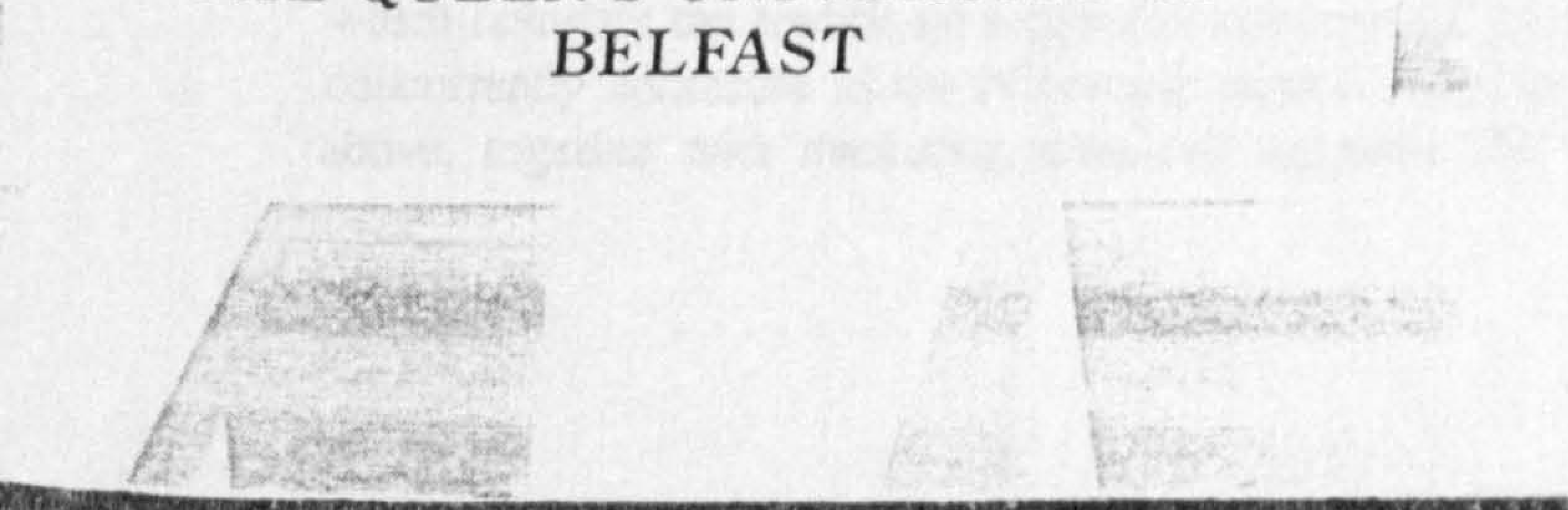

lowering costs, reducing lead times to market and producing high quality designs Monroy [3]. It also aims to diminish the difference between "ex post know committed cost" and "ex ante know committed cost" so developers, as early as possible in the development of the product know the consequences of their decision and thus way have a better possibility for minimising costs or to reach the best cost/benefit ratio of the project. The ideal situation then, of course, would be that the developers already "from the outset" know all committed cost or consequences. But it is more than what it can be saved by the full knowledge of committed costs. It depends on the specific situation, the specific organisation and the existing known means for achieving concurrent engineering. This paper investigates the appropriate methods that can effectively support Concurrent Engineering for Global Manufacturing through a benchmarking survey, ESPRIT 7752, IMS Test Case 3 "Global Concurrent Engineering (GCE)".

BENCHMARKING CONCURRENT ENGINEERING STRATEGY

Methodology

Over 320 companies were identified, and from those 150 distinguished organisations and companies were approached as suitable candidates to participate in the GCE survey. The selection of 150 companies was based on two major factors; firstly the Authors had a reason to understand that a concurrent engineering strategy in one form or another to had been implemented and secondly, these companies were actively manufacturing and marketing in a number of countries. The questionnaires developed and designed so as to address a wide range of issues to establish how GCE is exercised in the various organisations. Those aspects are technical issues, management issues and psychological issues. The questionnaires were designed in such a way to allow examination of different factors for New Product Development Projects. To ensure that suitable feedback is achieved finite, logical and quantitative types of questions were included in the survey questionnaires. The combined questionnaire is organised into three sections: (i) Corporate level; (ii) Management issue; and (iii) Psychological issues. The corporate level is addressed by a questionnaire developed and managed to examine corporate policies, strategies and practices in the implementation of GCE and the organisation of product development in the company. The corporate level survey is directed towards senior management. The second level of analysis examines the relationships between management and project teams. This level of analysis focuses on factors determining the effectiveness of GCE practices at the development program and project level. It surveys project team leaders, design and manufacturing team members, and managers working directly with project teams. The third level of analysis, the infra-project level, examines the internal operation of the teams. These issues are focusing on the R&D/Design, manufacturing interaction on the teams and their locations. It also examines the team's satisfaction issues. All the sets of questionnaires were tested and validated before release to participants.

The strength of the IMS-GCE research concept is that it allows for the linkage of these three levels of analysis within each company. Corporate or business unit strategies and policies can be linked directly to project team decisions and processes, which can be directly linked to summary and individual measures of team satisfaction, cohesion, and commitment. This design is based on a Global Concurrent Engineering approach which is multi-level and comprehensive. It allows for the hypotheses concerning the relative merit of different CE strategies and policies in influencing the outcomes of specific development projects, both in terms of meeting business goals and in terms of worker and management satisfaction with the development process.

Categories of CE Benchmarking

The essence of benchmarking is based on competitive performance according to other external perspectives. It is no longer limited only to comparison with competitors, but also aims to gain competitive advantage. It is the process of comparing business practices and performance levels between companies (or divisions) in order to gain new insights and to identify opportunities for making improvements Chambers and Pickering [4]. The greatest benefit is likely to be achieved by focusing on those areas of the business that are critical in driving competitive success. Emphasis is placed on understanding the processes that deliver performance and best practices in relation to those processes. Benchmarking helps to set strategy and identify new techniques. It also maintains the stimulus for continuous improvement. The key for best benchmarking practice should emphasis on understanding the actual performance of the business rather than just comparing results. There are several methods and categories of comparison to identify differences in performance levels and practices, some of the categories implemented in this project were:

❶ Functional Benchmarking: which compares between similar functions in different industrial sectors such as Design in Automotive, Aerospace, Telecommunications, etc.

❷ Customer Benchmarking: this category compares the company goals and performance against customer expectations. It monitors whether the company strategy and goals are based on customer expectations or not. For instance, is the organisation endeavour to improve quality and reduce product lead time while the customers preferring lower product cost.

❸ Competitor Benchmarking: which is a comparison between functions or performance and practices in similar industries. For instance, the current NPD strategy from two companies in the same sector.

❹ Generic Benchmarking: investigating the whole strategy and practices of industries, in order to understand and learn from their practices in different functions. Our research concentrates on generic benchmarking as it is the most useful approach.

The Generic Benchmarking Analysis

1. Strategies of the Industrial Sectors Involved in the Benchmarking

Companies and Organisations involved in the questionnaire have a wide variety of products, practices, goals, and views. This makes the final analysis of the collected data useful in achieving global benchmarking amongst the different industrial sectors (as shown in figure 1). The collected data was categorised into industrial sectors, this classification has enabled the authors to compare activities of companies from different industrial sectors together in order to get a broader view of adopted practices, and to identify differences in performance levels. It also facilitated the process of various types of benchmarking (functional benchmarking, competitor benchmarking, and internal benchmarking) to be carried out. The divergence of the product nature, primary goals, NPD challenges, and product and process design between the sectors was significant. For instance, the major goals of aerospace companies were the shortening of product lead times, the company's practising CE call it Simultaneous Engineering because it requires performing all operations in an interactive and parallel way; team working; DFX; or even Project Management approach. Other companies whom have heard only about it without practising it, call it multi-disciplinary teams approach. However, the name is not the essence, but the methodology, the co-operative product development, and achievements are important. However, in the analysis framework, the use of multi-functional teams was considered as a vital element of CE. Various types of tools and techniques were used to support the concept of CE, most of the companies (82%) have been using total quality management (TQM), management reorganisation (52%), collocations of functions (44%), and continuous improvement.

3.1 Steps Taken for Implementing Concurrent Engineering

Due to the diversity of the industrial sectors involved in the survey, in terms of product nature, size of the company, major goals of each company, the steps taken to implement CE varied from one Company to another. Figure (3) shows the various common steps taken by the companies towards implementing CE. Functions co-location was considered by 44% of the enterprises as the first step, while 52% of the companies had to reorganise the management structure of their company to utilise CE. These results match the findings of the UK Design Council Survey [5], more than 50% of the organisations use product teams and co-located their team members in order to achieve better communications and decision making. IT tools were used by almost 30% of the companies to support CE, but it doesn't represent the strongest factor as some might expect. Training for staff was mentioned as a vital step, 56% of the companies have highlighted the importance of this factor.

3.2 Barriers to Concurrent Engineering Implementation

The main barriers reported during the changes to CE were management problems (41%) and resistance to change (41%). Poor definition and lack of expertise or information were highlighted by 33% of the companies as major difficulties to persuade their people of the concept. Similar outcomes were stressed in the UK Design Council's survey in 1993, 70% of the companies participated in that survey mentioned that lack of CE information and difficulty in knowing where to start as crucial barriers to CE implementation. The same survey has also revealed that 60% of CE knowledge was gained through self-learning. These results and others emphasise the necessity for training and development for the management as well as for individuals to achieve a clear understanding of the philosophy. In this survey 41% of the companies indicated that lack of training was a major obstacle. On the other hand, companies which have been practising CE have focused on team building skills and the use of total quality management (TQM), and quality function deployment (QFD), the techniques which entails the involvement of customers and suppliers as principal players or the key role to the business success. However, lack of Information Technology tools was hardly mentioned as a barrier, only 4% of the companies reported IT as a problem they have to overcome for CE implementation, which means that CE requires changes in the organisational issues rather than the technical one.

3.3 Benefits Gained from Practising Concurrent Engineering

Significant CE benefits were reported in the questionnaire as shown in Figure 4, the most frequent benefit reported was shorter time to market (70%). In addition other benefits such as; improving communications (59%); improved product quality (56%); reduced development costs and better management (33%); reduced design change (48%) effecting shorter ramp up time and improving the company's competitiveness. The Design Council Survey 1993 has also shown that late design changes can seriously affect development costs, as they are probably the most expensive to implement. It also showed that between 30% to 50% of the companies were suffering from the high level of engineering rework CE also increased the profit of 30% of the companies. All these benefits are very much interrelated and lead to other achievements such as increasing marketshare and customer satisfaction.

CONCLUSIONS

The key factors for how to make CE works were investigated. Technical, managerial, and psychological issues were identified as principal areas for adopting CE philosophy. Managerial and organisational issues in terms of communications between the organisation and its customers, suppliers and amongst the teams within the organisation itself; training required to make the team understand the new strategy in order to have a common goal. The essence is having a co-operative team rather than collocated functions which is considered as the first step towards implementing the concept.

In this survey two types of benchmarking have been encompassed. First, is the Generic benchmarking which investigates the different types of practices employed by different companies and organisations. The second is the Functional benchmarking which compares between similar functions in different industries, for instance design methodology in an Aerospace company and a design in a Automotive company. The results have shown that the requirements of lower costs, better quality, shorter times, and customer satisfaction are the driving force for new product development. Rapid change in technology has caused the customers to expect reduced lead time. In order to increase market share companies have to produce a high quality and cost effective product. However, for some manufacturers maintaining high quality is as important as gaining extra market share (luxury car manufacturers). The strong lesson drawn from the experience of the companies practising CE for several years is that it requires comprehensive training in team building, reorganisation, common understanding to the company's target, and leadership.

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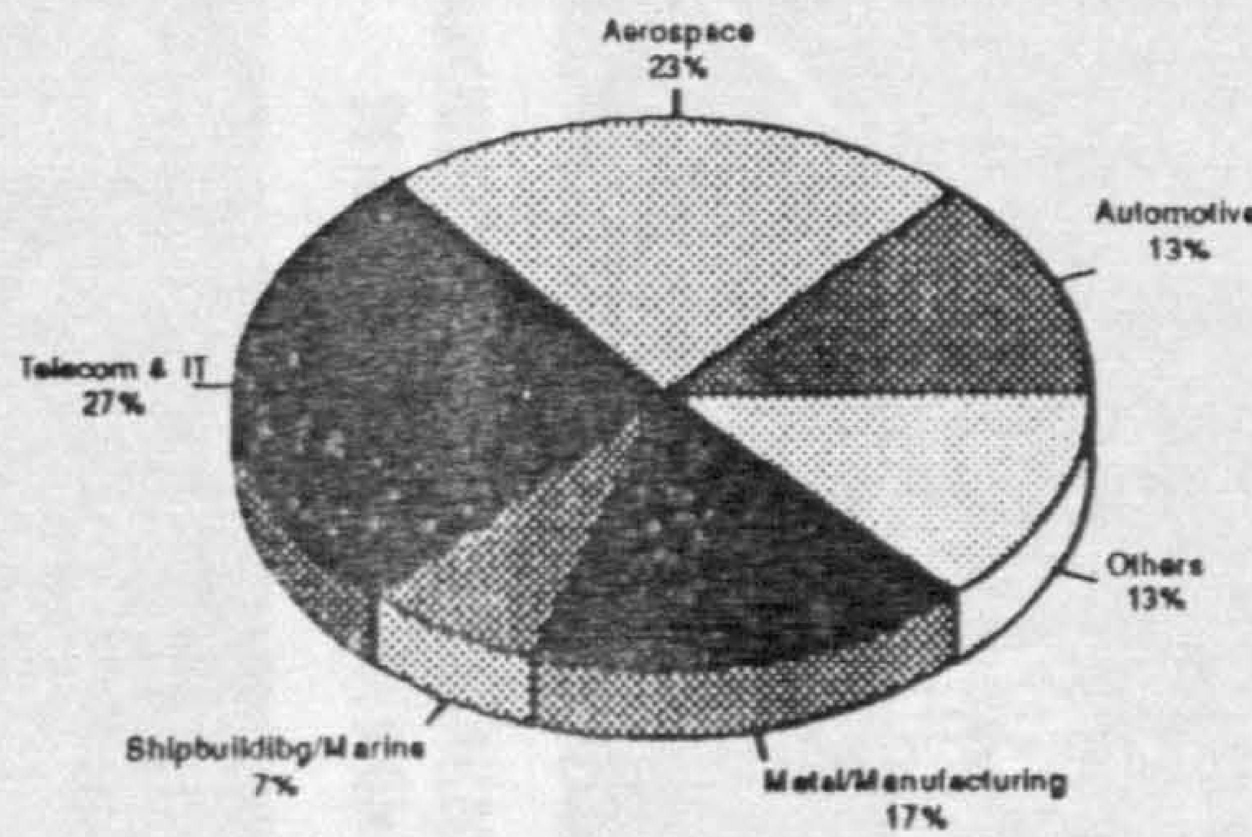


Figure (1) Breakdown of Industry Sectors Participated in the Survey

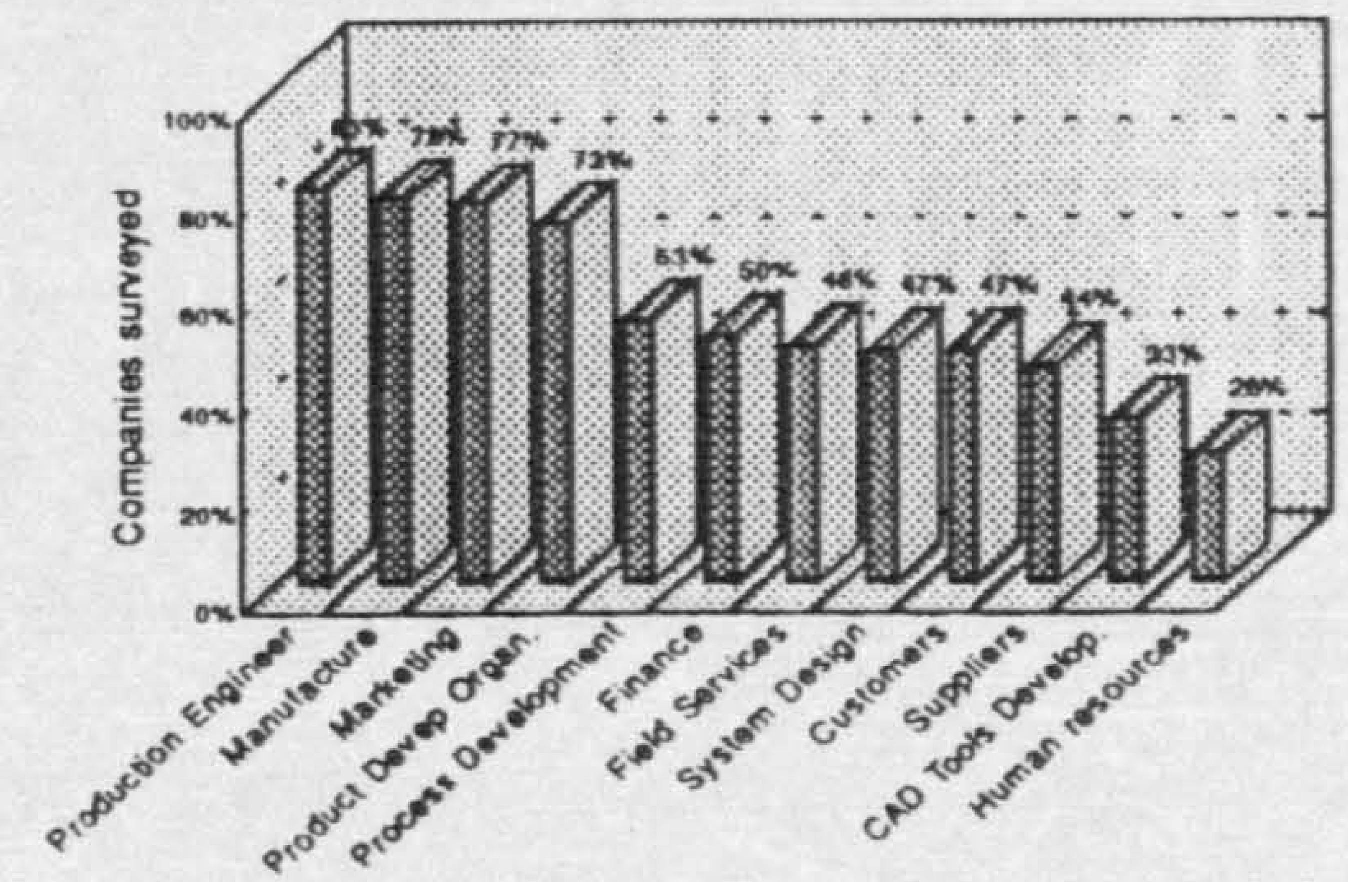
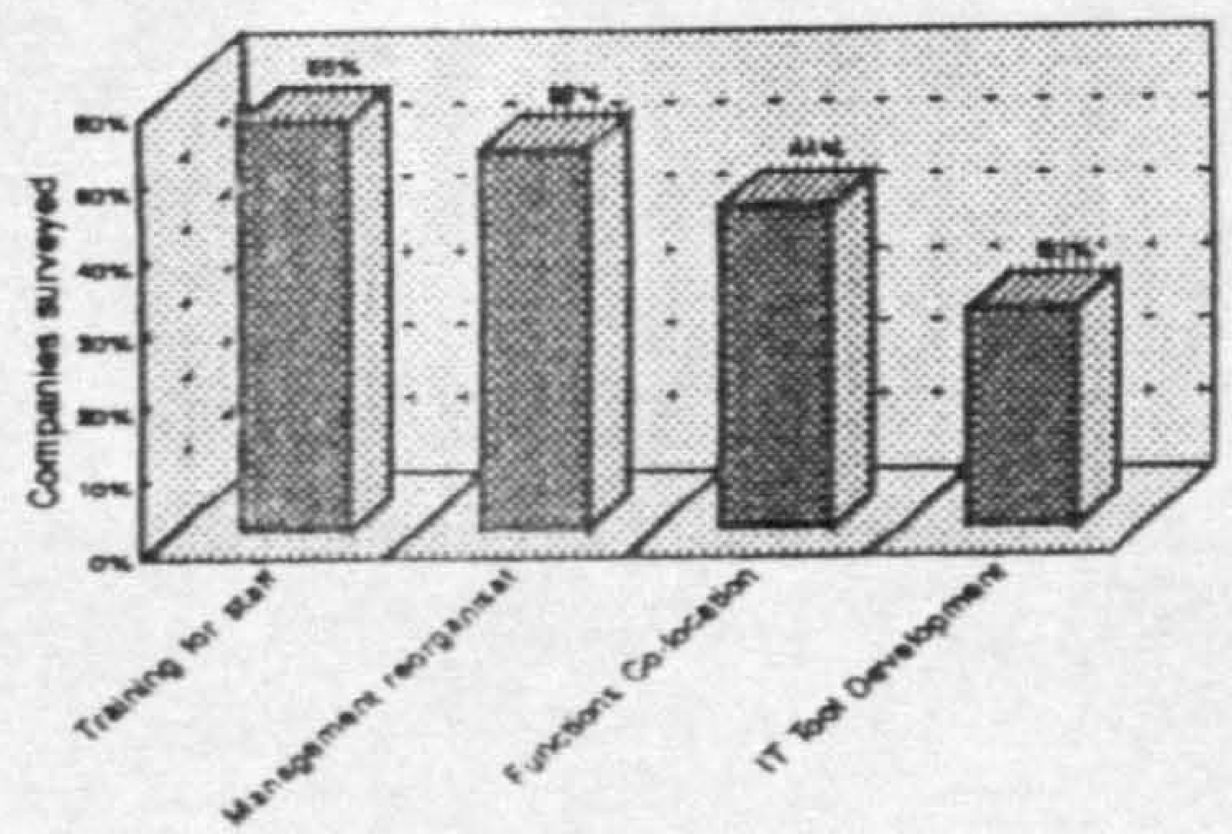


Figure (2) Distribution of the Departments input to NPD



Figure(3) Steps taken for Implementing CE

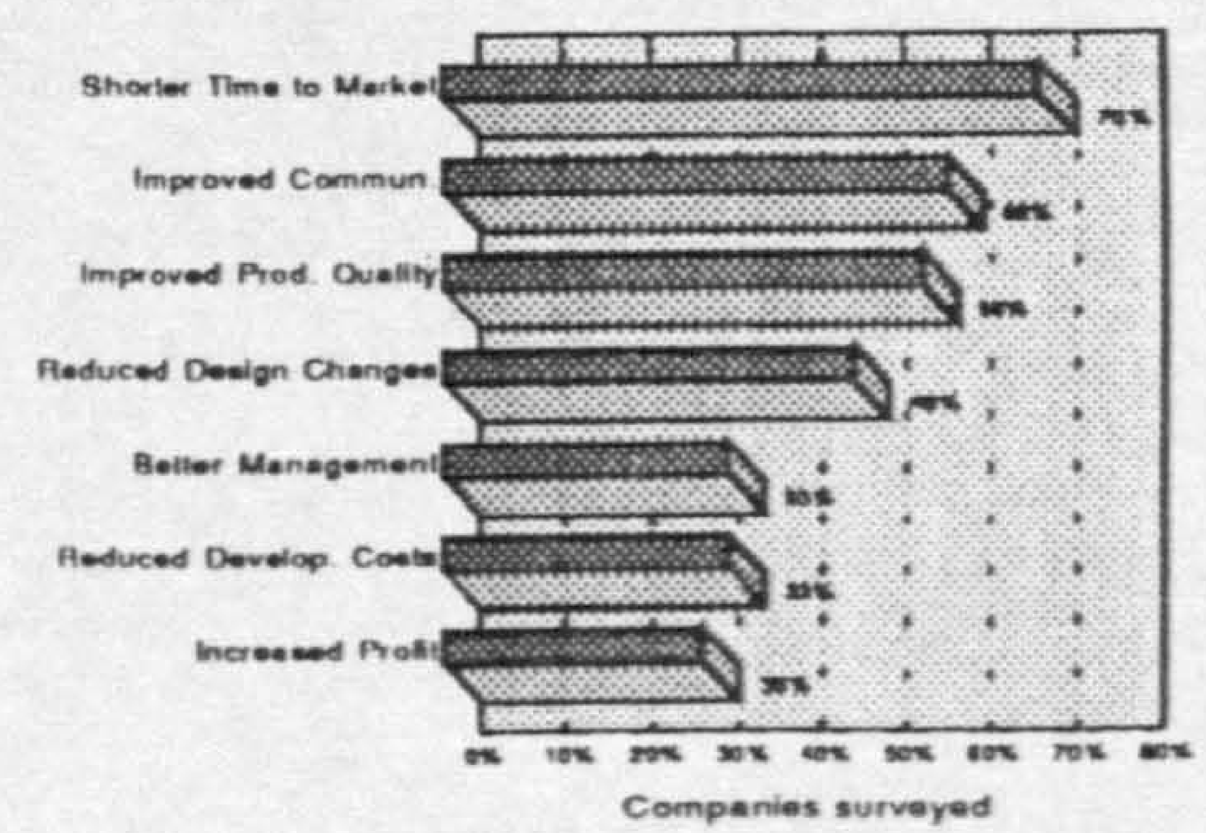


Figure (4) Benefits of using CE strategy

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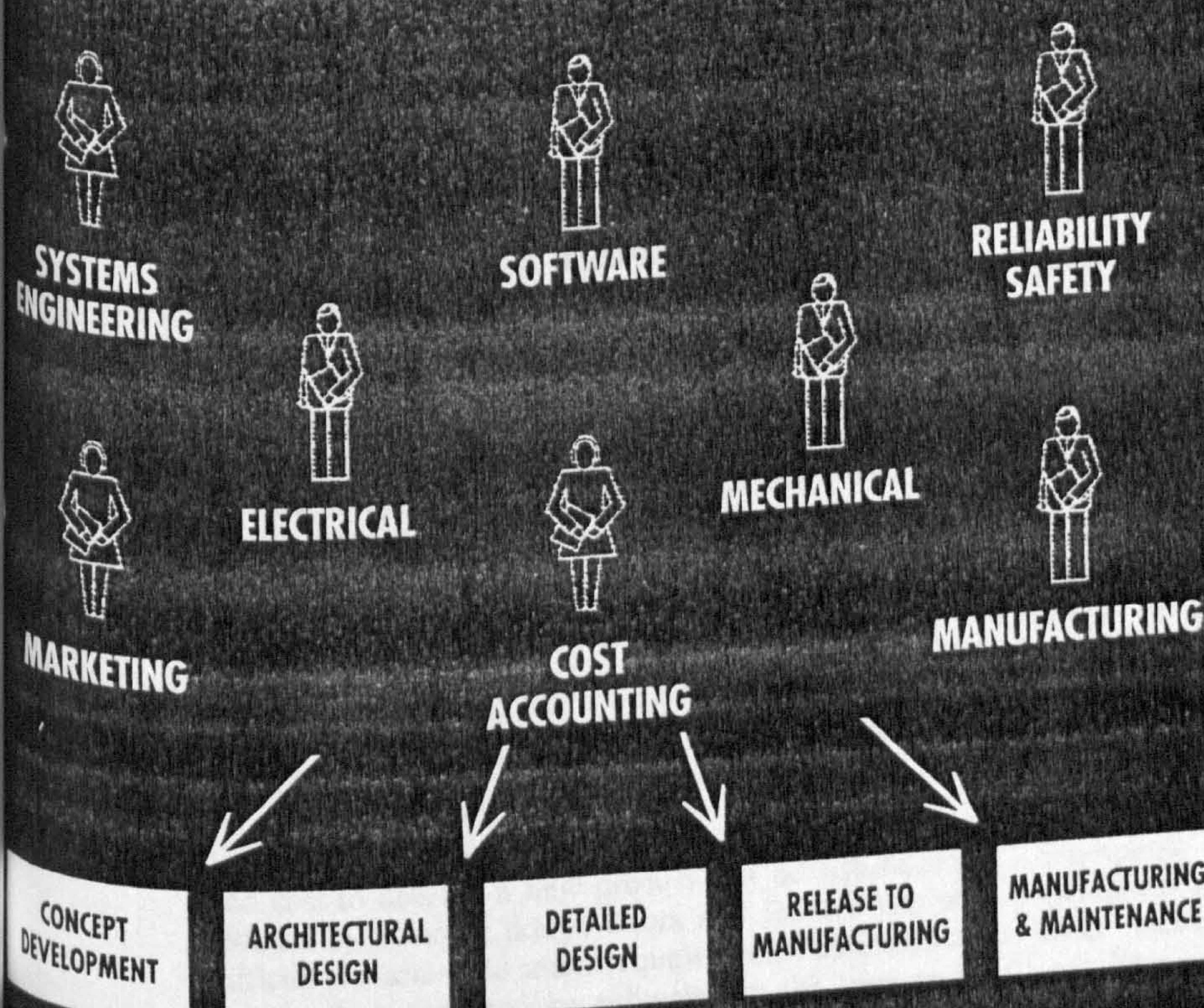

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A FEATURED BASED DESIGN ENVIRONMENT FOR CONCURRENT ENGINEERING

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ABSTRACT

Concurrent Engineering (CE) addresses the issue of developing the lowest cost design strategy of a part by concurrently taking into consideration different product life-cycle concerns during the product development process. It also involves design, materials, manufacturing processes and cost, taking into account later stage considerations such as testability, serviceability, quality, and reliability. A company cannot meet quality and cost objectives with isolated design and manufacturing engineering operations. In this paper a prototype system which links a Knowledge-based System (KBS) shell with a solid modelling system and allows the user to create a set of design features is discussed. The KBS captures topological and geometrical information about the model features and estimates the machining cost for these features at each design stage. It then recommends how to improve the design and eliminate potential defects. The complete system enables designers to improve the manufacturing process, reduce production costs and significantly improve the quality of the product. This paradigm has been seen as a great success towards achieving the goals of Concurrent or Simultaneous Engineering strategy.

INTRODUCTION

In Concurrent Engineering (CE) environments, the time and cost to develop a new product can be significantly reduced by avoiding design errors and features that are difficult to machine. In addition questions are addressed on how product costs can be estimated at the very early design stage so that the product's profitability can be assessed. A significant amount of attention is currently being directed towards implementing and developing different methods for attaining the above target. One of these methods is using the concept of design for manufacturability (DFM) which addresses the issue of developing the lowest cost design of a part by taking into consideration not only the functional and structural requirements of a part, but also machining, assembly, maintenance and testing requirements of a part. The basic idea is to execute product design and process planning simultaneously rather than sequentially. This issue has gained national attention as an important subject of investigation in both industrial and academic institutions. (Jo et al. 1990) proposed a conceptual model of the CE environment as shown in figure (1). In this figure, the outer layer of the CE level, product modellers are advanced which can provide designers with the capability to invoke any tools in the inner layer to evaluate or optimize their designs. The core of the wheel is the control logic which involves steering of various CAD tools to provide a variety of services, helping to find a globally satisfied design.

(Moore et al. 1990 and Wong et al. 1991) have introduced a cost prediction system that can be used in a CE environment. (Lu and Subramanyan 1988) presented a CE design environment based on knowledge-based systems to design product and process simultaneously. The main components of their system are features database, manufacturability advisor, and user interface. (Sutherland et al. 1988) proposed a methodology for a CE strategy which incorporates machining processes modelling and the design of experiments to find robust product/process design in terms of a set of factors such as part material and machining conditions. (Abdalla and Ikonopisov1993) have developed a knowledge-based system, which can be used to generate a process plan for the production of machined piece-parts, given a feature-based part description. The system enables process planners to optimize process plan, and thus reduce the manufacturing costs. (Alder and Ishii 1989; Nevins and Whitney 1989; and Ishii et al. 1988) proposed slightly different approaches for implementing the concept of design for manufacturability or Concurrent Engineering. Their approaches and others have shown that the benefits which can be achieved by implementing the concept of Concurrent Engineering are significant. However, in general, the implementation of Design for Manufacturability, Design for Cost or Concurrent Engineering strategy has been shown to be a non trivial task inherent with difficulties which have to be overcome before the full benefits of the technique can be achieved. The major problem is efficient and effective extraction of feature information from a solid modeller (Choi et al. 1984). A second problem is the integration of a Computer-aided Design (CAD) system with a Knowledge-based System (KBS). The final problem to be overcome is constructing a KBS which can give a first order cost estimate for product designs early at the design stage.

AN ENVIRONMENT FOR CONCURRENT PRODUCT AND PROCESS DESIGN

Automated Feature Recognition

Modern CAD systems represent part geometry in terms of low level geometric and topological entities such as faces, loops, etc. High level abstraction of the component that relates to design function or manufacturing characteristics is not provided. This research illustrates an approach to extract these desired higher level abstractions. The approach provides hope that a design can be automatically evaluated for manufacturability during the iterative design process. The solid modelling Computer-aided Design (CAD) System, Pro/Engineer (Parametric Technology 1991) was chosen for developing the proposed system. The reason for the choice of Pro/Engineer was that it offers designers the opportunity to think and work with "meaningful" engineering features such as slots, holes, chamfers, etc. This provides an easy to use front-end capable of capturing the designer's intent more fully than with the traditional CAD systems. It also contains assembly and manufacturing modules. The strong points of Pro/Engineer are seen firstly as the ease with which a solid model containing the designer's intent may be constructed and hence captured. Secondly, the strength of the interface mechanisms gave a resolute approach to integration with other CAD/CAM software. Finally, there is the manipulation of user defined features.

For an interactive design process, the modeller must provide sufficient external interface capabilities to allow both the modeller and an external program to interact in a unified manner. Pro/Develop, the programmatic interface of the Pro/Engineer database, and bespoke software written for C and Unix environments, have been implemented to develop this system. The developed system provides the following facilities: "(i) direct access to the solid modelling system database for unique and specialized engineering applications; (ii) direct access to the database to derive automated feature recognition". This technique contains an interface enabling users to interact with the system effectively and efficiently. Designers can create features such as holes, slots, rounds, fillets, etc.

Knowledge Representation

The advent of the Artificial Intelligence systems has introduced a wide variety of knowledge representation schemes such as frames, rules, logical terms, etc. A Knowledge-based System (KBS) toolkit (KEE) developed by Intellicorp (Intellicorp 1989) was chosen for both knowledge representation and decision making in this research. The system was built on a SPARC station (SUN4). KEE supports frame based objected oriented programming and rule based reasoning. These rules consist of a series of necessary and sufficient conditions. They have been implemented in this research for recognising the feature type (holes, slots, drafts, etc.) by matching the available feature's data with predefined feature characteristics. After defining all the features, geometrical and topological, the system records and represents them in groups according to their types.

The Proposed Feature-based Design Approach

The Knowledge-based system toolkit (KEE) together with the CAD system (Pro/Engineer) were seen as an ideal medium for achieving the goals of this research. Consequently, the integration between the solid modeller and the reasoning system was considered as a crucial step towards achieving the target of this project. KEE itself does not provide an external communication capability but allows complete access to Lucid's Common Lisp language. Common Lisp in turn supports a foreign language interface to communicate with PASCAL, FORTRAN, and C languages. These external languages can then open, read, and write files. On the other hand, Pro/Engineer can communicate to the outside world through the programmatic interface Pro/Develop. Figure (2) illustrates the Overall System Architecture of the link between the CAD system and the KBS tool (KEE). In a typical scenario, when a request for a geometric data query is received, KEE will invoke the proper Lisp method which calls a C routine with a command string as an argument. The C routine then puts the command string in a file and goes into a wait and check cycle until complete information comes back from Pro/Engineer. When the C routine receives all the data requested back from Pro/Engineer, another Lisp program is already loaded, and will start immediately to send the data back to the KBS.

The CONSTRUCTION OF THE KNOWLEDGE-BASED SYSTEM

The inheritance hierarchy of the reasoning system KEE has been used to model the product features as described blow. There are two root classes: the first one is the product features and the various product.features can be categorized as: form.features, material.features and precision.features. The second one is the facility features, and the various facility features can be categorized as: cutting.tool.features, machine.features, fixture.features, and material.handling.features.

Product Features

Form Features

Form.Features are presented as subclasses of the product.features, and can be classified broadly into two subclasses: compound and primitive.features (see Fig.3). Compound.features are broadly divided into two units: external and internal.features. External.features can be further classified into subclasses such as drafts, fillets, and rounds. Each unit has a slot which contains various information about the unit characteristics such as depth, length, radius, etc. Primitive.Features are divided into two subclasses: concentric and non-concentric.features. Concentric.features are rotational features whose axis of rotation coincides with the primary axis of rotation of the part. Non-concentric.features are rotational features whose primary axes of rotation are different from, and non-coincidental with the primary axis of rotation of the part. Further extensions to the form feature hierarchy can be done in the future to distinguish between the type of primitive features that make up a compound feature.

Precision Features

Precision Features are the class of features used to indicate how much a part can vary from its true form and still be acceptable.

Material Features

The material composition, grade, and properties of a part are specified by the material.features hierarchy. The material characteristics of a part are specified by indicating the appropriate material from this class of features.

Manufacturing Facility Feature Inheritance Hierarchy

The inheritance hierarchy underlying the frame based system was used to model manufacturing facility features. The root class is facility.features and the various facility features can be categorized as: cutting.tool.features, machine.features, fixture.features, and material.handling.features.

Machine.features and material.handling.features are used to characterize the various machines and material handling equipment available in a facility. The attributes of machine features describe the various types of machines available in the manufacturing cell such as Milling Machines, Turning Machines, etc.

Fixture.features are used to describe the structural and functional characteristics of various fixtures and fixtures components used in the manufacturing cell. Cutting.tool.features are used to describe the structural and functional characteristics of various cutting tools and cutting tool components.

KNOWLEDGE-BASED SYSTEM CONSTRAINTS

A number of constraints about the existing manufacturing facilities are represented inside the KBS using the rules of KEE. These constraints are implemented to bound the machining processes and to show the feasibility of the part during the design stage and before making the final prototype. In this context manufacturing criteria have been utilised as rules to approve constraints. Using the manufacturing rules, the designer is able to examine whether the designed part can be manufactured with the available manufacturing facilities or not. For instance, if the designer specifies a hole with a specific diameter (d_h) the system will compare this diameter with the predefined diameter range "$D_{min} < d_h < D_{max}$". Warning is given in the case of inconsistency or invalid dimensions (hole diameter is too big or hole diameter is too small). Consequently, the designer can select other appropriate dimensions. This can take place at the very early stage during designing the product; implementation of this strategy avoids manufacturing surprises.

A set of manufacturing rules and criteria are used to determine machining operations, such as turning, drilling, milling, in addition to non-conventional techniques like Electrochemical, Laser, etc. An example for selecting the appropriate operation required to make a particular feature according to the predefined rules or constraints is shown blow:

If

(The Feature is a hole) and
(The Diameter of the Hole $D_h > 0.002$ in) and
(The L/D "Depth over the Diameter" < 4) and
(The Tolerance of the Hole < $0.005\ D_h$) and
(Additional Rules)

Then

(LASER is selected)

Laser is one of the advanced hole making techniques which have been accepted practice for a number of years for drilling fine holes.

Cost Estimation and Process Plan Generation Procedure

In the last decade the impacts of technological advancement (IT tools, CIM, DFX, etc) have made significant changes in the methodology, strategy, utilization of engineering and manufacturing. Some of these tools and methodologies have been developed for supporting Concurrent Engineering philosophy, but most of them are based on conventional techniques for cost estimation which are not structured to adequately support the concurrent engineering strategy. In this research the proposed design environment overcomes the above deficiency, it consists of product design module, cost estimating module, and process planning module as shown in figure (4). After creating the component with the solid modelling system, the Feature Recognition System (FRS) defines and extracts the information needed for machining the component's features (slots, holes, etc. and their attributes such as dimensions, tolerances, etc.) and sends them back to the process planning system (PPS). Once the PPS receives the necessary information from the FRS, it starts to select the machining operations, machine tools, cutting tools, machining parameters. The system then sequences the selected operations and calculates the machining time, cost (Abdalla and Knight 1993), and examines the results with the desired goals (such as minimum cost). The system has been designed to enable users to obtain information about not only the total cost but also the individual cost elements such as turning cost, milling cost, drilling or reaming cost, tapping cost, centre drilling cost and setup cost. The system is utilising the manufacturing knowledge (rules, equations, etc.) for estimating the process cost and manufacturability of the component. If the cost of the product exceeds the targeted cost, then the system may suggest discontinuing the further development or redesigning the product. The system is developed in such a way that it collects data from various engineering activities in a CE environment and evaluates the design based upon the predicted costs of machining, assembly, material, testing, overhead and other drivers.

CONCLUSIONS

Concurrent Engineering has been seen as a successful strategy in elimination of waste, reduction in lead time for product development, improvement of the product quality and reduction of cost. The implementation of CE approach requires that all the engineering activities such as process planning, manufacturability, testability, cost estimation, engineering analysis, maintenance, assembly, etc, to be considered at a very early stage during the design, in addition to good communications and management. Achieving the above target necessitates integrating different Information Technology (IT) Tools (CAD/CAD, Knowledge-based System toolkit, CAE, etc). The integration will facilitate various activities such as analysis and refinement of product and process data. A new methodology to integrate a Knowledge based reasoning System with a Solid Modeller for design analysis and machining cost estimation has been demonstrated. The developed technique enables engineers to minimize the machining cost, improve the quality of the product, and to avoid any manufacturing problems as early and quickly as possible during the design phase.

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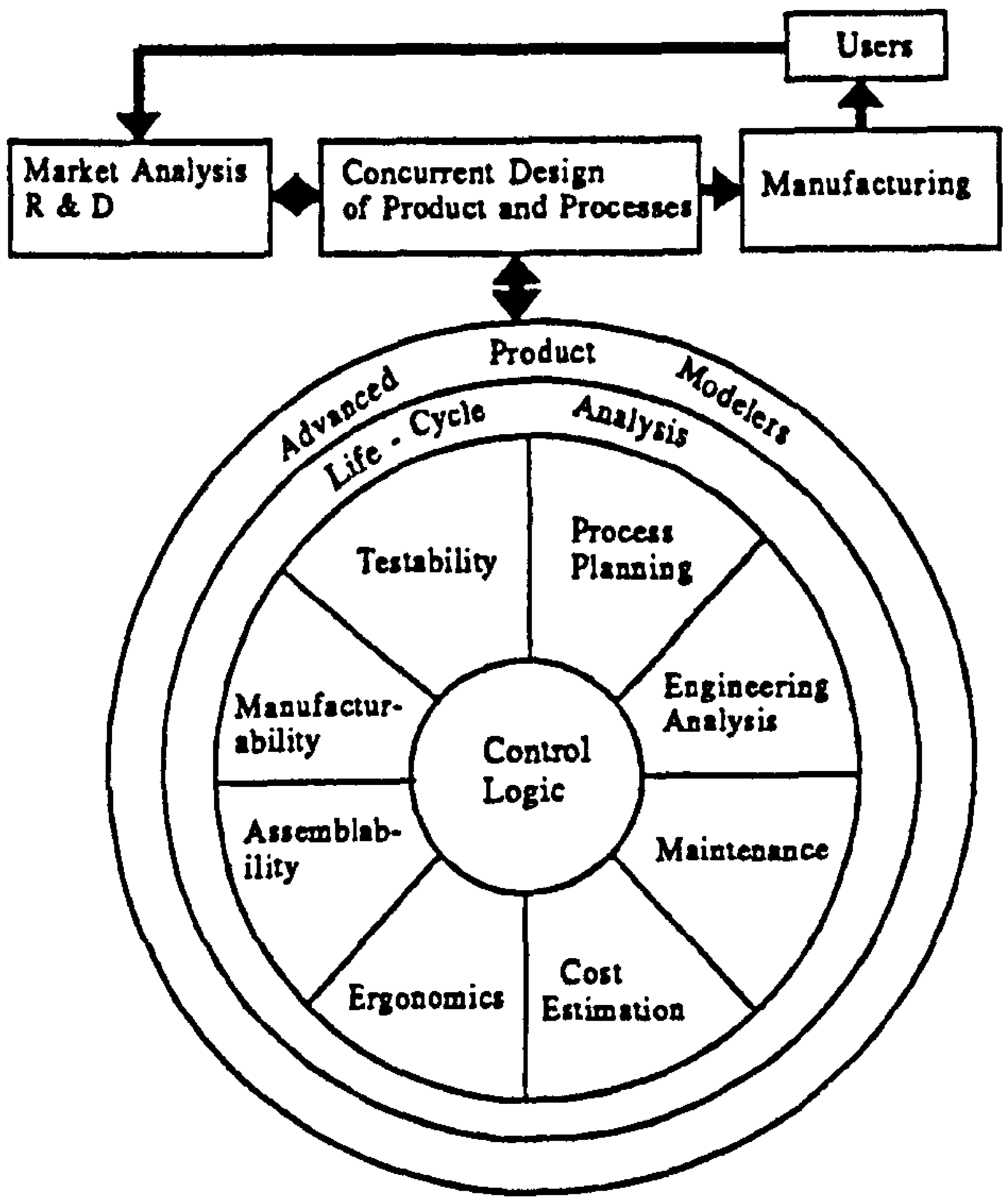

Fig.(1) Product development cycle employing Concurrent Engineering Strategy.

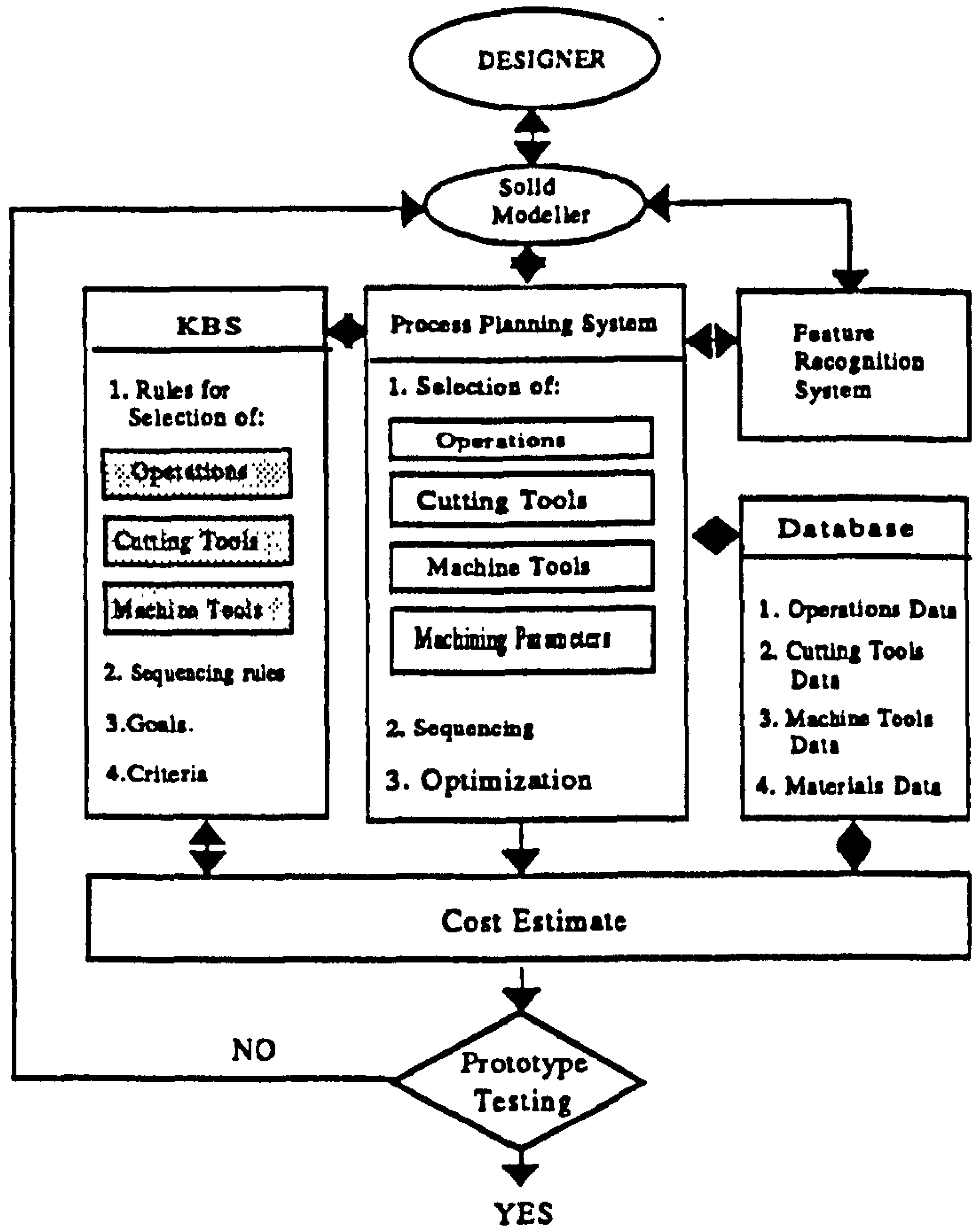

Fig (4) A Concurrent Engineering Design Environment

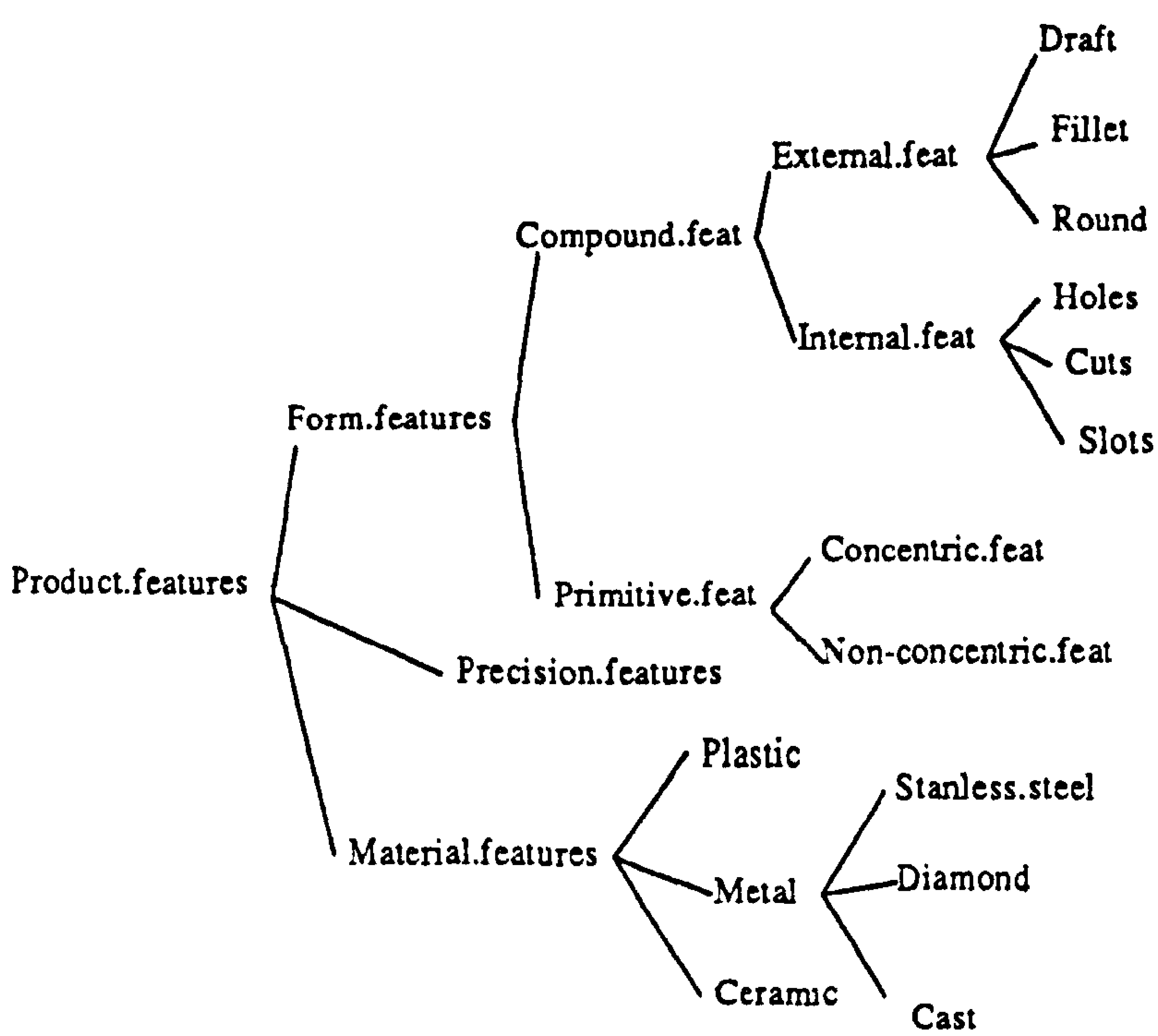

Fig.(3) Product Features Inheritance Hierarchy.

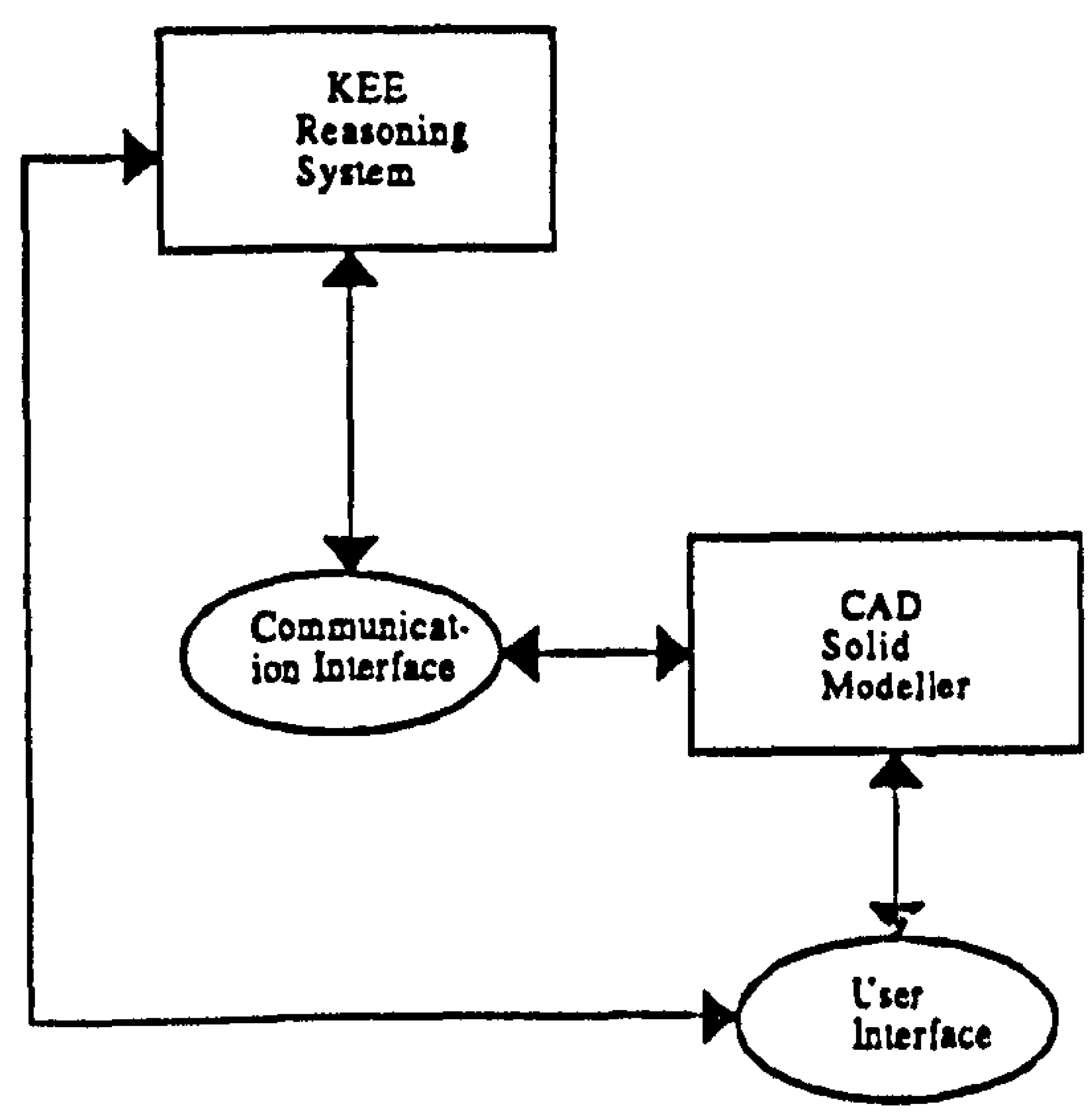

Fig.(2) Overall System Architecture of the CAD & Knowledge-based System Communication.

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PROFESSOR J A G KNIGHT ROOM 2N3
HEAD OF ENGINEERING RESEARCH

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ADVANCES IN MANUFACTURING TECHNOLOGY VII

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Automated Feature Recognition for Process Planning

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Abstract

The enormous benefits of Automated Process Planning (APP) Systems have created much interest. The major obstacle for achieving the goal of APP is the lack of schemes capable of defining the suitable information for applications such as Design for cost, Design for Assembly, Process Planning, scheduling, etc. This research aims to develop a Knowledge-based System, which can be used to generate a process plan for the production of machined piece-parts, given a feature based part description. An approach is developed for describing the work piece specification in terms of geometry, dimensions, tolerances, etc. This information has to be determined precisely at each manufacturing operation in order to produce the finished part with the right specification. The proposed process planning system enables process planners to optimize process plan, and thus reduce the manufacturing cost.

1. Introduction

In manufacturing, process planning can be defined as the preparation of a detailed plan for the production of a part or assembly. The selection and sequencing of the operations needed to transform raw material into a finished part are the main objectives. Once products have been designed, the process planner has a very significant impact on the cost, quality, and rates of production. Well formulated process plans can provide products of the required quantity in the desired quality on the planned schedule and at a possible minimal cost.

Traditionally process plans are produced by planners who extract features from blueprints and match a set of operations to make each feature. Figure (1) shows the process planning approach currently used on CNC machines (Chang, 1985). The drawback of this approach is the dependence on the skills, experience, and the knowledge of the planners. It is also costly and does not consider the effect of the product design on the manufacturing cost. It does not have the capability of optimizing the product or the process design. Figure (2) illustrates the layout of the main process planning and database modules for the above approach.

During the last few years, attention has been directed at enhancing various schemes for knowledge-based process planing (KBPP) systems. Lenau and Lianchun 1993, have presented new ways of modelling products and processes based on the study of previous authors. The conclusion was that most of the authors emphasized the use of object-oriented representation, where features are used to improve the possibilities for integrating various activities in the process planning system. Others place accent on the features themselves. Pratt 1993 and Wierda 1991 focused on multiple applications of form features in the design and manufacturing cycle. They proved that feature based

models have potential to close the gap between design and process planning. Gindy et al 1993, presented a hierarchical structure for form feature definition and classification. A planning data model and an information structure were used to develop process plans for prismatic machined components; others stressed process planning strategy. (Joseph et al 1988) have suggested an automatic process planning system for rotational components using feature-based modelling to represent the work pieces and a "backward planning" as a strategy. Xiying et al 1989, introduced a Computer-aided Process Planning (CAPP) system. A multi-stage backward planning technology and heuristic searching strategy were used to create an interference engine. The conclusion is that most of the research used feature-based knowledge to create process planning expert systems, but did not give solutions for simultaneous improvement in product design and process planning.

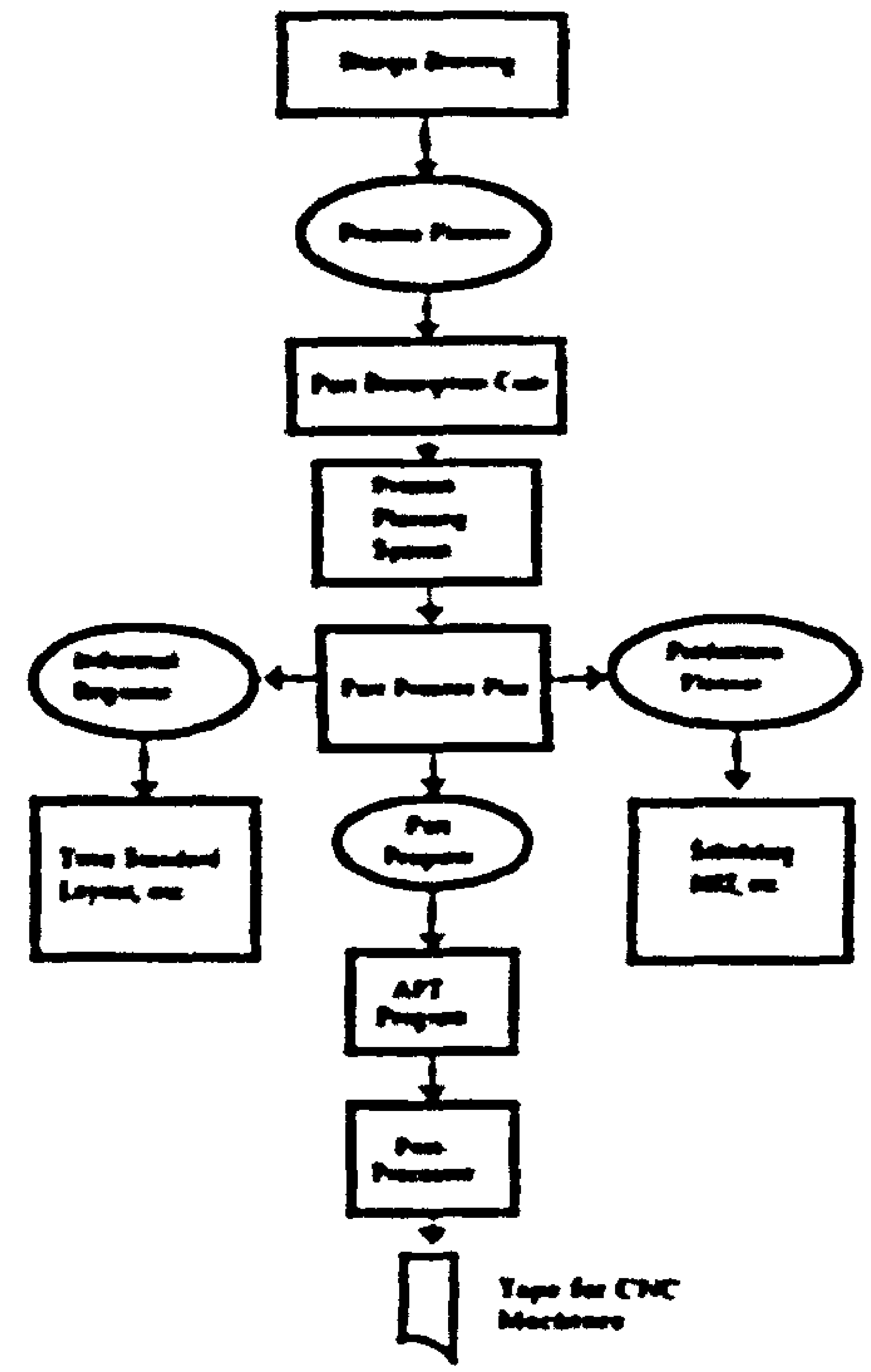

Figure (1) A Traditional Approach for CNC Machined Process Planning.

2. The Proposed Process Planning Technique

Well designed products with low machining costs are desirable. A Process Planning approach based on Concurrent Engineering (CE) strategy has been extended to process design and evaluation at an early stage of product design. Figure (3) shows an architecture for the suggested Concurrent Engineering Process Planning (CEPP) model. The main components are Feature Recognition, Knowledge-based, and Process Planning System which have been integrated into an environment for effective and efficient implementation. The structure of the above components are described as follows:

2.1. Feature Recognition From a Solid Modeller

Modern CAD systems represent part geometry in terms of low level geometric and topological entities such as faces, loops, etc. High level abstraction of the component that relates to design function or manufacturing characteristics is not provided. Abdalla and Knight 1993, developed an approach to extract these desired higher level abstractions. The approach provides hope that a design can be automatically evaluated for manufacturability during the iterative design process. The solid modelling Computer-aided Design (CAD) System, Pro /Engineer was chosen for developing the proposed system. It offers designers the opportunity to think and work with "meaningful" engineering features such as slots, holes, chamfers. This provides an easy to use front-end capable of capturing the designer's intent more fully than with the traditional CAD systems. It also contains assembly and manufacturing modules. The strong points of Pro/Engineer are seen firstly as the ease with which a solid model containing the designer's intent may be constructed and hence captured. Secondly, the strength of the interface mechanisms gave a resolute approach to integration with other CAD/CAM software. Finally, there is the manipulation of user defined features.

For an interactive design process, the modeller must provide sufficient external interface capabilities to allow both the modeller and an external program to interact in a unified manner. Pro/Develop, the programmatic interface of the Pro/Engineer database, and bespoke software written for C and Unix environments, have been implemented to develop this system (Abdalla and Knight 1993). The developed system provides the following facilities: "(i) direct access to the solid modelling system database for unique and specialized engineering applications; (ii) direct access to the database to derive automated feature recognition". This technique contains an interface enabling users to interact with the system effectively and efficiently. Designers can create features such as holes, slots, rounds, fillets as shown in Figure (4)

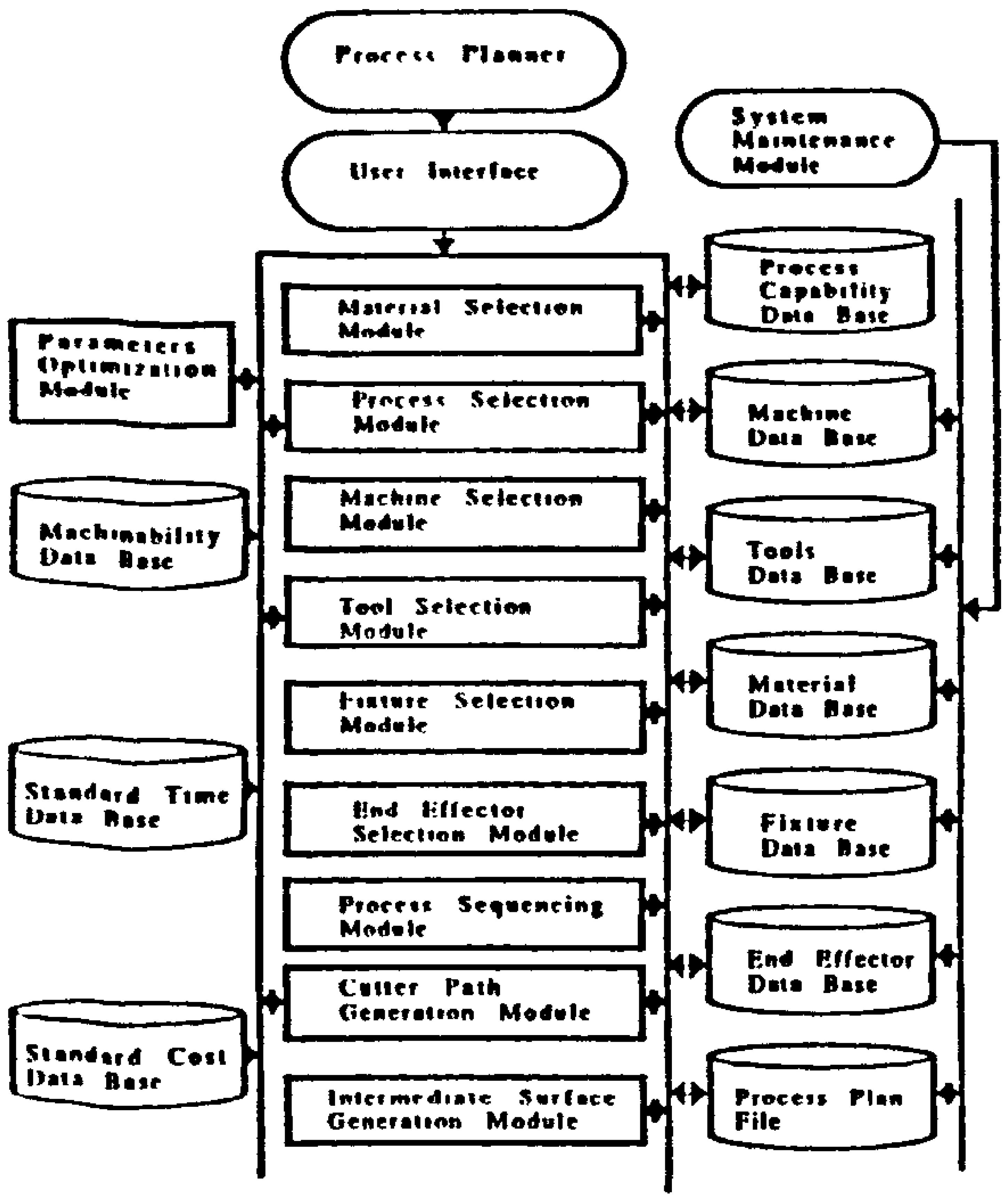

Figure (2) Process Planning Modules and Data-base.

2.2. Knowledge-based System (KBS)

A major need in designing a KBS for Process Planning is that designs evolve. It transforms concepts into process designs and then products. Comprehensive Design for manufacture (DFM) methodology and tools should give DFM functionality at various levels of detail design. More detail of process considerations results as the design evolves

2.2.1. Knowledge Representation

Process Planning knowledge requires a Knowledge-based System using rules and frame based methods. For example, a knowledge-base which involves the interaction between surface roughness and dimensional accuracy can be represented by a rule based scheme. Geometric features of the product can be handled by a frame scheme. Discussions with companies who have experience of Knowledge-based systems (KBS) tools showed that the strongest contender for building KBS is Knowledge Engineering Environment (KEE) tool. KEE supports frame based objected oriented

programming and rule based reasoning. Each object in KEE is represented as a single frame, called a unit, and each unit is composed of slots. Each slot can contain data or a procedure describing the characteristics and behaviours of a particular object. The knowledge-based system toolkit (KEE) has been implemented for representing the manufacturing facilities and the product features in hierarchy tree.

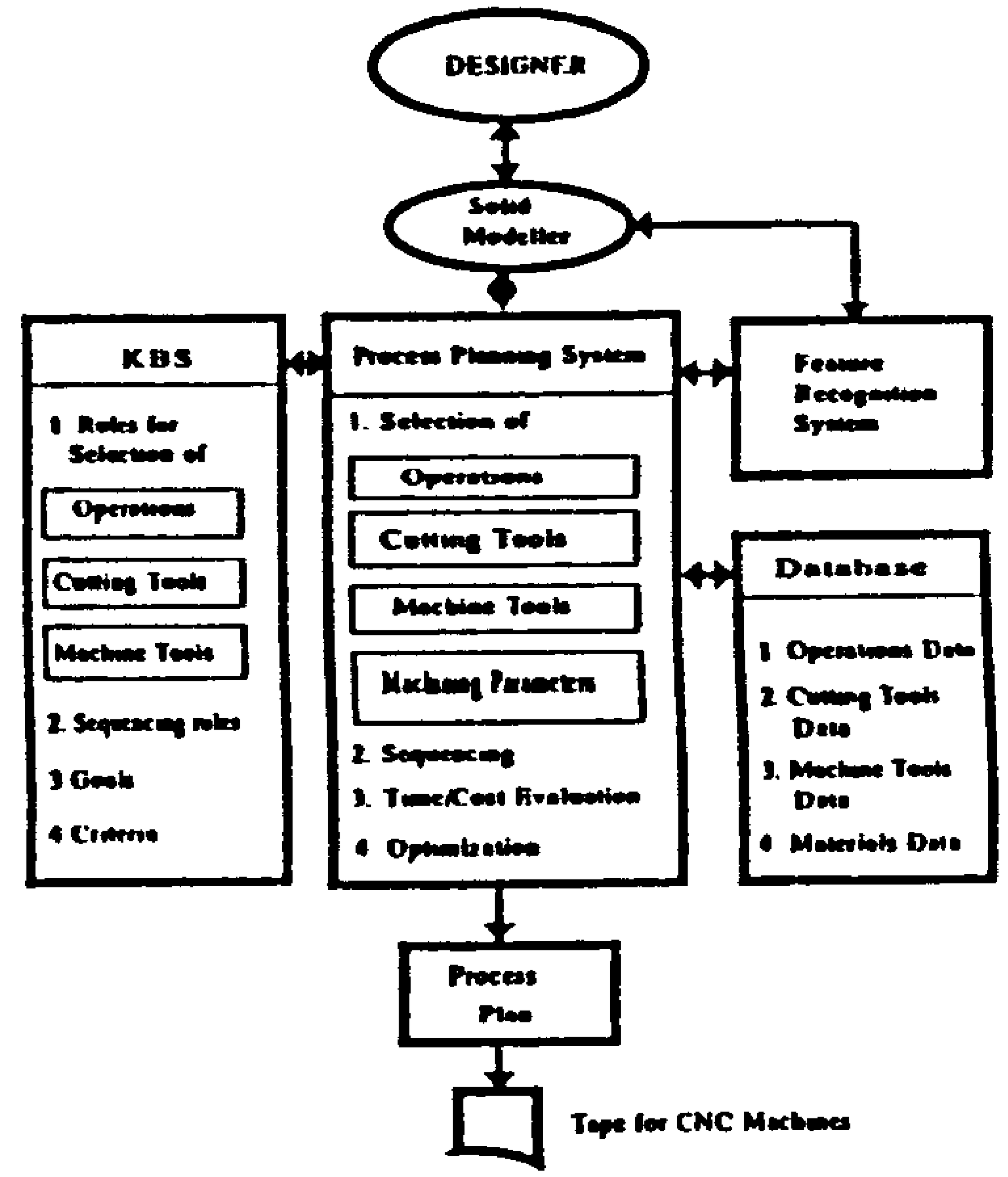

Figure (3) An Architecture of CE Model for Process Planning

2.2.2. Database

The Process Planning Database consists of material & machining operations data (for example, accuracy and surface finishing corresponding to a particular machining operation). It also contains information about machine tool capabilities, form generation functions, work envelope, and technological output in terms of accuracy, feed rate, cutting speed, power, etc.

2.3. Process Planning System (PPS)

The proposed CE model evaluates all decisions connected with component design and matches them with the knowledge-base rules. It proposes possible changes of the inapplicable design features. It uses part features, manufacturing knowledge, machine tool data, cutting tool data, material data, and goals as initial information for generating the required process plan. The system is utilising the manufacturing knowledge (rules, equations, etc.) for estimating the process cost and manufacturability of the component

After creating the component with the solid modelling system, the Feature Recognition System (FRS) defines and extracts the information needed for machining the component's features (slots, holes, etc. and their attributes such as dimensions, tolerances, etc.) and sends them back to the PPS. Once the PPS receives the necessary information from the FRS, it starts to select the machining operations, machine tools, cutting tools, machining parameters. The system then sequences the selected operations and calculates the machining time, cost, and examines the results with the desired goals (such as minimum cost). Users can interact with the system concerning modifying the generated process plan if it does not match the desired goals. Above all, the CAD solid modelling and the Knowledge-based system were linked together using the interprocess communication shared memory and semaphore (Abdalla and Knight 1993).

3. Conclusions

Automated Process Planning techniques are at an early stage of development. Most of the existing process planning systems rely on manufacturing planners for describing the product and process characteristics manually. The ability to define the part geometry and topology is a crucial step in establishing an automated process planning technique. This research illustrates a technique that overcomes these deficiencies and gives more close integration for design and manufacture. It reduces lead time, process and product cost while maintaining high product quality through continuous improvement of the machining processes.

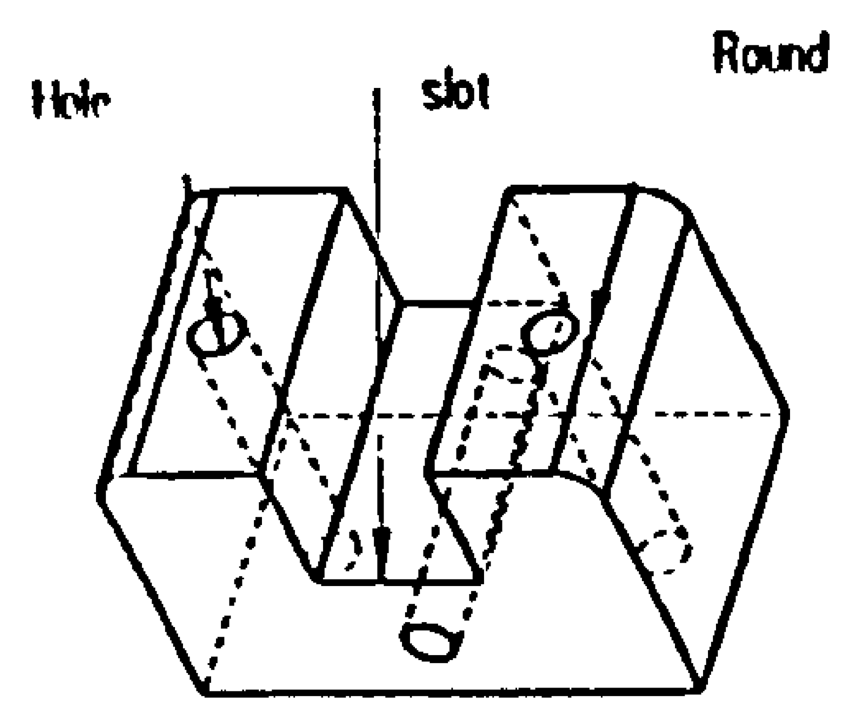

Figure (4) An Object and its Form Features

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Manufacturing Feature Identification for Prismatic Components from CAD DXF Files

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Abstract

A novel approach for interfacing Computer Aided Design (CAD) and Computer Aided Process Planning (CAPP) for prismatic components is discussed. The analysis presented forms part of a CAD interpreter under development, which uses the industry standard DXF (Drawing Interchange File) file format to translate CAD drawings into a manufacturing feature based output file, to be directly used by a CAPP system. Algorithms for identifying the external profile of a prismatic component and allocating surface roughness values to surfaces requiring finishing, are discussed.

1. Introduction

Two of the major activities within the development phase of industrial products is product design and planning of production. These two activities are often carried out in isolation within companies. Today's competitive situation requires that product development times are shortened, product quality improved, costs reduced, and environmental consequences minimised. To realise these goals, integration of the design and planning activities is considered essential.

Describing components by the use of features is seen by many as the key to genuine integration of the many aspects of design and planning of manufacture, particularly in a modern computer-controlled environment incorporating Computer Aided Design (CAD) and Computer Aided Process Planning (CAPP) (Brimson and Downey 1986). Features originate in the reasoning processes used in various design, analysis, and manufacturing activities (Cunningham and Dixon 1988) and are frequently strongly associated with particular application domains. Hence there are many different definitions of features. A broad definition in the engineering domain is given by (Pratt 1988) as: "A feature is a region of interest on the surface of a part".

The use of features on the design side ("design features") could relate to the fulfilment of functional requirements, the building of a geometric model, or as preparation for design analysis activities such as finite element analysis. On the

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Reduction-in Category		Design Rule
EFFORT	→	Ease HANDLING
ADJUSTMENT	→	Improve/simplify LOCATION
VARIETY	→	Aim for STANDARDISATION
ON-LINE	→	Limit component NUMBERS

Figure 3. Design Rules for Changeover

The relationships between 'reduction-in' categories and design rules for changeover are by no means mutually exclusive. The important contribution of the strategy is that it enables more focused assessments to be made. The rules represent top level objectives for the designer as he or she works to improve the manufacturing system in which changeover occurs.

Conclusions

This paper draws a distinction between design and method as polar extremes on a spectrum of changeover improvement activities. This greatly assists in determining where SUR effort should be concentrated, where there are arguments in favour of emphasis on both design-biased and method-biased improvement. Any assessment of where the emphasis should be placed on the spectrum should be related to an overall improvement target.

Research by the authors has shown that a typical improvement team will need to be adequately supported as it moves to tackle more complex design issues.

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A KNOWLEDGE-BASED PROCESS QUALITY CONTROL PLANNING SYSTEM FOR DESIGN FOR MANUFACTURABILITY

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Quality is imperative for success in today's international market. At one time mass inspection was seen as the way to achieve product quality but it is no longer a realistic option. Rather, the manufacturer must match the capability of production processes to design requirements, and ensure that the processes remain in control during the manufacturing stage. This requires the use of process capability indices and Process Quality Control Plans. The above goal can be achieved through implementing the concept of Design for Manufacturability (DFM), which gives simultaneous consideration to factors influencing manufacturability, reliability and hence cost. Typically, these factors include manufacturing processes, design specifications and materials. The proposed approach employs DFM methodology for estimation of process capability indices and the preparation of quality control plans system.

Introduction

There is a strong body of opinion that quality is now the major determining factor in business corporate success. A number of research papers have confirmed that improved quality leads to reduced costs and prices which result in increased market share and a secure future and improved return on investment. According to Feigenbaum (1991) personal life styles and business practices now mean that quality and not price is the main purchasing criterion. Feigenbaum goes as far as describing quality as "the single most important factor for success in international markets". Business commentators in the popular press increasingly acknowledge the importance of quality in the search for competitive advantage, Roberts (1992).

Quality can be defined as, consistently conforming to customer requirements at the lowest cost", Porter (1990). Such a definition shows that inspection of manufactured goods is no longer a viable option. To inspect out components that do not conform is both time consuming and expensive and also implies that manufacturing capacity is used to produce product that ultimately will be scraped. Clearly inspection and meeting customer requirements at "the lowest cost" are not compatible. Equally such is the reliability of inspection, in identifying and rejecting non-conforming products, that inspection and "consistently" meeting customer requirements are not compatible. However, achieving conformance at the lowest cost demands a knowledge of the variability of manufacturing processes. This knowledge will enable the selection of most cost effective process capable of consistently producing conforming components. The process capability indices C_p and C_{pk} are commonly used to express the relationship between the process performance and the specification limits, Sullivan (1986) and Kane (1986).

$$C_p = (USL - LSL)/6\sigma;$$
$$C_{pk} = \min[(USL - \bar{x})/3\sigma, (\bar{x} - LSL)/3\sigma]$$

Where:

USL is the Upper Specification Limit,
LSL is the Lower Specification Limit,
σ is the standard deviation (A measure of the process variability or repeatability), and $\bar{x}$ is the process mean (A measure of the process setting or accuracy within the specification limits).

A knowledge of the numerical values of these capability indices enable the suitability of a process to be assessed. A process with an indices of less than 1.33 would normally be considered unacceptable for the manufacture of automotive components Ford Motor (1990). Whilst a process with a value between 1.33 and 2 may be considered acceptable, special sampling arrangements would be required during manufacture to ensure adequate confidence in the process, Porter and Oakland (1990). This paper describes how the concept of DFM can be implemented to enable the use of capability indices during the design phase to assist in the selection of a manufacturing process. This work enables designers to select processes and specification limits that will ensure consistent conformance to the specification at the lowest cost. Within this work attention is focused on the indices C_p.

The Design for Manufacturabity (DFM) Environment

The DFM concept is a process not a product for converting the traditional sequential time phased product life cycle to a parallel process which concurrently addresses the aspects of design, analysis, and manufacturing. The philosophy is geared towards, reducing manufacturing problems, lowering costs, reducing lead times to market, and producing high quality designs. To achieve this goal, it is necessary to tackle the following three classes of problems: first, traditionally sequential phases in the production cycle must be restructured so that they can be performed simultaneously; second, functional barriers between departments, which have created a strict sequential flow of activity, time wasting and inter-departmental communication, should be removed; and finally, appropriate Information Technology (IT) tools enabling the new approach to be implemented should be developed and adopted. Since, the application of IT can effectively provide support to the proposed DFM approach by integrating the disciplines such as CAD, CAM, CAPP and CAE in which computers already have a well established role.

Why Design for Manufacturability ?

Before we can address the issues of DFM and the approaches that can be adapted, it is important to first identify when and how this design environment can be used and what does the conventional model look like. A sequential model was

extended from Molloy's (1993) and Wong et al (1991) models to cover product specification and analysis. In this technique seven important stages can be identified, namely: market needs, product specification, product design, analysis, process planning, manufacturing and sales. This sort of model had suited industries for centuries, but in the days when the sales market was considerably larger then the suppliers could satisfy and this sequential form of departmental communication was acceptable. But in the present day 'first to market' environment, this form of communication is too compartmentalized, assuming the design is the domain of the designer, manufacturing the domain of the manufacturing engineer and so on. The consequence of this can easily justify DFM or Concurrent Engineering (CE), when you consider that the majority of life cycle costs are committed at the conceptual phase. This was the topic of research conducted at the Rensselaer Polytechnic Institute and reported in a paper by O'Flynn and Ahmad (1991), which highlighting the impact that design has on total product life cost. The research also indicated that 75% of a product's cost are committed by decisions made early in the conceptual design phase. Their model also describes the design knowledge build up during the product life cycle. It is this knowledge that DFM is attempting to address at the design stage to implement any down-line changes necessary as early as possible in the cycle.

The Proposed DFM Approach

An integrated Knowledge-based system toolkit (KEE) and a CAD system (Pro/Engineer) was developed by Abdalla and Knight (1994) for establishing a DFM environment. The integration between the solid modeller and the reasoning system was considered as a crucial step towards achieving the objective of this project. KEE itself does not provide an external communication capability but allows complete access to Lucid's Common Lisp language. Common Lisp in turn supports a foreign language interface to communicate with PASCAL, FORTRAN, and C languages. These external languages can then open, read, and write files. On the other hand, Pro/Engineer can communicate to the outside world through the programmatic interface Pro/Develop. In a typical scenario, when a request for a geometric data query is received, KEE will invoke the proper Lisp method which calls a C routine with a command string as an argument. The C routine then puts the command string in a file and goes into a wait and check cycle until complete information comes back from Pro/Engineer. When the C routine receives all the data requested back from Pro/Engineer, another Lisp program is already loaded, and will start immediately to send the data back to the KBS. This system has been enhanced to estimate the capability indices for each process, which assist the user in selecting the most appropriate manufacturing processes.

A Case Study

The design of an automotive brake pedal was considered as a case study, to show the principals of this work. The pedal incorporates an integral pivot in the form of a cylinder. Within the cylinder are two critical dimensions, length, which must be maintained with a tolerance band of 0.5mm, and internal diameter, which must be maintained within a tolerance band of 0.04mm. Nine processes available to the pedal manufacturer are shown in table 1,(all tables are given at the end) together with their natural tolerance band and comparative cost per unit of metal removal (1 being the lowest and 10 the highest).

Cylinder Overall Length

During the design stage the knowledge based system extracts the required CAD data and identify the shape created as a cylinder. Then it investigates the CAM database for selecting suitable available processes for manufacture the cylinder. For each process the capability indices Cp and comparative costs to a given length is shown in table 2.

Internal Bore

Following abstraction of the internal bore and investigation of the CAM database processes, five processes suitable for the manufacture of the internal bore can be identified. These processes together with capability indices and comparative costs are shown in table 3.

User Interface Information

In this example both the features can be satisfactorily manufactured using available processes and hence the designer would be given the information shown in table 4.

Conclusion and Future Work

This research has discussed a technique for Quality Control Plans for mechanical components within a Design for Manufacturability Environment. The proposed approach ensures that manufacturer must match the capability of production processes to design requirements, and ensure that the processes remain in control during the manufacturing stage, which dictates the implementation of the Process Quality Control Plans and process capability indices. It can be concluded that DFM concept leads to the following benefits reduced lead times, product costs, higher product quality and matching customers requirements.

Further Work

1 Features are considered in isolation we should consider some means of optimising process selection allowing for other features on the same part.

2 Process capability feedback into CAM database.

3 Optimising the user interface

4 Advising the designer when significant cost savings are available by a reduction in the required tolerance

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Table 1 Process Available

Process	Natural Tol. Band (mm)	Comp. Cost Per Unit Of Metal Removed	Feat.1 Hole	Feat.2 Slot
Saw	0.8	1		
Drill	0.25	1	Yes	
Plane	0.125	4		
Mill	0.1	2	Yes	Yes
Turn	0.15	2		
Bore	0.05	4	Yes	
Ream	0.01	5	Yes	
Broach	0.01	8	Yes	Yes
Grind	0.02	10	Yes	Yes

Table 2 Process for the Manufacture

Process	Natural Tol Band (mm)	C_p	Comp Cost	Remarks
Grind	0.02	25	10	High cost
Mill	0.1	5	2	Satisfactory
Turn	0.15	3.33	2	Satisfactory
Saw	0.8	0.625	1	Inadequate

Table 3. Summary of processes for the manufacture of the inter. bore

Process	Natural Tol. Band (mm)	C_p	Comp. Cost	Remarks
Broach	0.01	4	6	Satisfactory
Ream	0.01	4	5	Satisfactory
Bore	0.025	1.6	4	Adequate but required N=10
Drill	0.8	0.05	1	Inadequate

Table 4 Summary of designer interface data

Part	Feature	Process	C_p	Comp. cost	Preferred
Brake Pedal	Cylin. Length	Turn	3.33	2	Yes
		Mill	5	2	No
		Grind	25	10	No
	Inter. Bore	Ream	4	5	Yes
		Broach	4	6	No

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A KNOWLEDGE BASED SYSTEM FOR EFFECTIVE COST DESIGN BASED ON A SOLID MODELLER

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Abstract

This paper presents a new technique which bridges the gap between engineering design and manufacturing. A company cannot meet quality and cost objectives with isolated design and manufacturing engineering operations. To be competitive in today's marketplace necessitates a single engineering effort from concept to production. The essence of the Concurrent Engineering approach is, therefore, the integration of product design and process planning into one common activity. In this paper we discuss a prototype system which links a Knowledge-based System (KBS) shell with a solid modelling system and allows the user to create a set of design features. The KBS captures topological and geometrical information about the model features and estimates the machining cost for these features at each design stage. It then recommends, how to improve the design and eliminate potential defects. The complete system enables designers to improve the manufacturing process, reduce production costs and significantly improve the quality of the product.

Introduction

Today, within the prevalent distributed product development environment, fast changing and highly competitive economies are forcing industries world-wide to seriously consider various methods to reduce product development time and cost. Manufacturing costs form a major component of the total cost of a part and a number of different measures can be taken to reduce this cost. For example, reductions can be achieved by automation, material handling, new materials, tools and processes, more effective layout scheme, and assembly techniques. Most of these measures are highly dependent on the design of the part and can be fully established only when taken into consideration while the part is being designed. To achieve this goal the barriers between departments, which have created a strict sequential flow of activity, time wasting and inter-departmental communication, must be removed. Designers often consider that their main task is to create part designs to meet structural and functional requirements. Therefore, the product is not designed on manufacturing bases, this can possibly create many manufacturing problems. This can be avoided if manufacturing criteria are considered during designing the part.

A significant amount of attention is currently being directed towards implementing and developing different methods for attaining the above target. One of these methods is using the concept of design for manufacturability (DFM) which addresses the issue of developing the lowest cost design of a part by taking into consideration not only the functional and structural requirements of a part, but also machining, assembly, maintenance and testing requirements of a part. The basic idea is to execute product design and process planning simultaneously rather than sequently. This issue has gained national attention as an important subject of investigation in both industrial and academic institutions. Alder and Ishii [1], Nevins and Whitney [2], and Ishii et al. [3] proposed a slightly different approaches for implementing the concept of design for manufacturability or Concurrent Engineering. Their approach and others have shown that the benefits which can be achieved by implementing the concept of Concurrent Engineer are significant. However, in general the implementation of design for manufacturability/design for cost strategy has been shown to be a non trivial task inherent with difficulties which have to be overcome before the full benefits of the technique can be achieved. The major problem is efficient and effective extraction of feature information from a solid modeller [5]. A second problem is the integration of a Computer-aided Design (CAD) system with a Knowledge-based System (KBS) [6,7]. The Final problem to be overcome is constructing a KBS which can give a first order cost estimate for product designs early at the design stage [8,9,10].

Information Technology (IT) Tools Selection

The Computer Aided Design System

The solid modelling CAD system (Pro/Engineer) [13] was seen as a most suitable CAD package as the base for developing the proposed system. Pro/Engineer was chosen for the following reasons: it offers designers the opportunity to think and work with "meaningful" engineering features, for example slots, holes, and chamfers, so providing a convenient to use front-end capable of capturing the designer's intent more fully than with the traditional CAD systems. It also contains assembly and manufacture modules.

The Knowledge-based System Toolkit

A Knowledge-based System toolkit, Knowledge Engineering Environment (KEE) developed by Intellicorp [11], and the Lisp Language were chosen to build this system on a SPARC station (SUN 4). KEE supports frame-based-objected-oriented programming and rule-based reasoning as shown in Figure (1). Each object in KEE is represented as a single frame, called a unit, and each unit is composed of slots. Each slot can contain data or a procedure which describes the characteristics and behaviour of a particular object. The objects of the application domain are represented in a hierarchial class-subclass-member structure. Attributes and methods of a class higher in the hierarchy can be inherited by classes at the lower hierarchy. Relations of an application domain can be represented by slots.

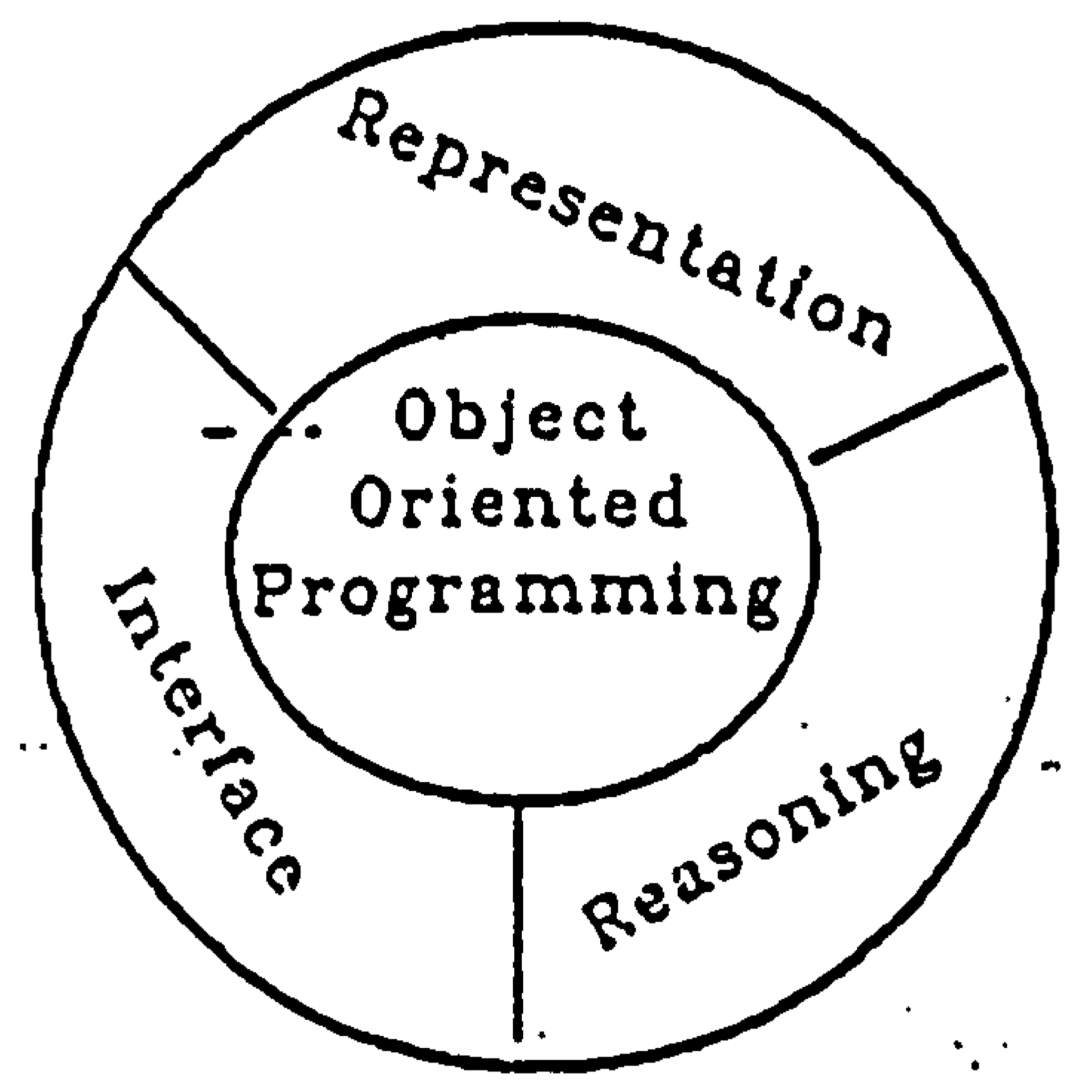

Fig.(1) The Basic Components of the Knowledge-Based System Tool (KEE).

and write files. On the other hand, Pro/Engineer can communicate to the outside world through the programmatic interface Pro/Develop. Figure (3) illustrates the Overall System Architecture of the link between the CAD system and the KBS tool (KEE). In a typical scenario, when a request for a geometric data query is received, KEE will invoke the proper lisp method which calls a C routine with a command string as an argument. The C routine then puts the command string in a file and goes into a wait and check cycle until complete information comes back from Pro/Engineer. When the C routine receives all the data requested back from Pro/Engineer, another Lisp program is already loaded, and will start immediately to send the data back to the KBS.

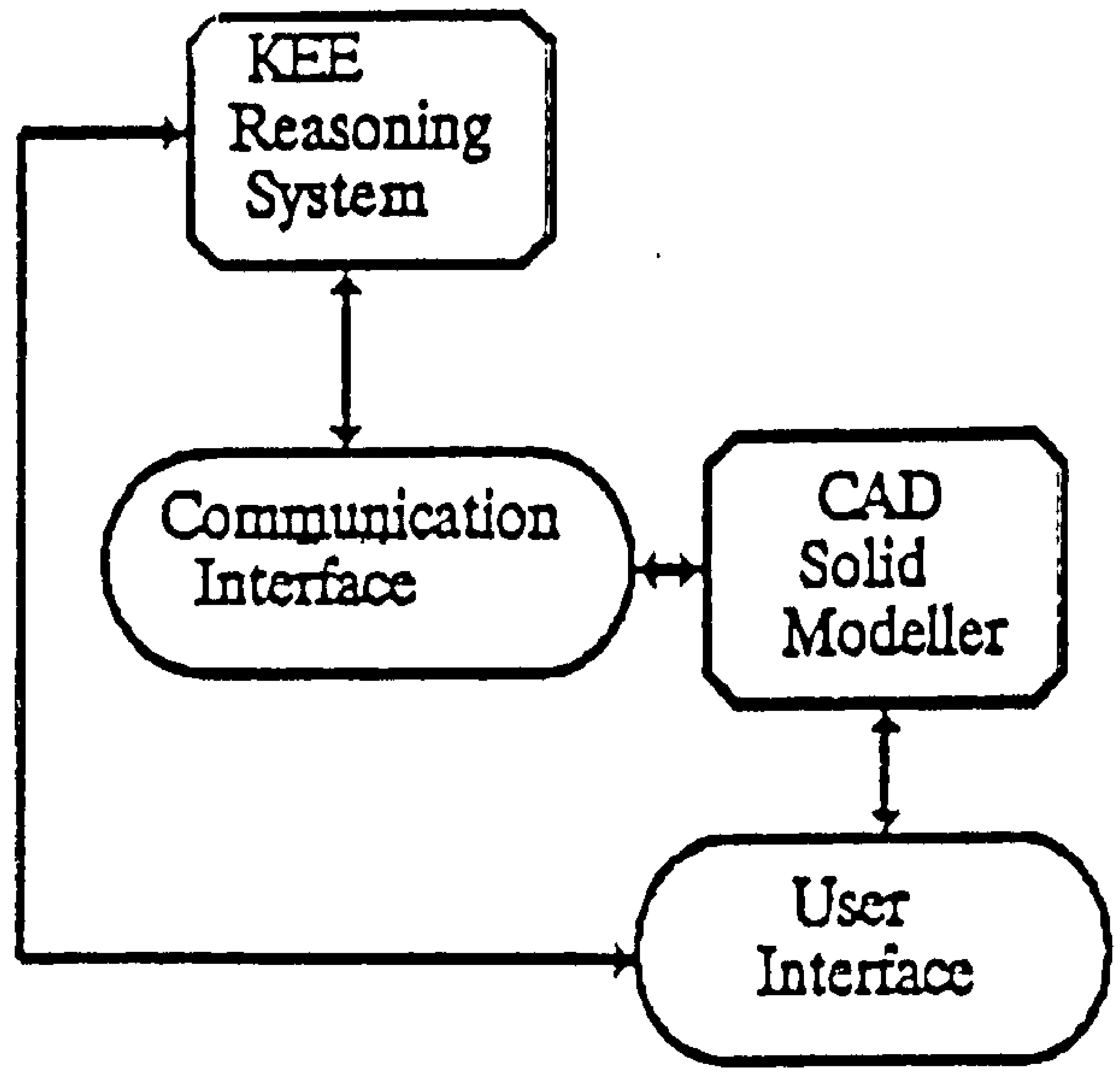

Fig.(3) Overall System Architecture of the CAD&KBS Communication.

System Operation

Once the user clicks on the UDF_Features Menu button the Pro/Engineer system forwards geometric construction data and feature descriptions through to KEE. In addition, feature embellishments are carried out as the data transfer takes place. KEE then acts on the received data and creates corresponding data structures to store the information for further reasoning, analysis and applications. This data is normally represented in an object-oriented form, consisting of geometric features and associated physical details. An analysis is then carried out which converts the physical features to a manufacturing feature structure.

The Construction of the Knowledge-based System

The inheritance hierarchy of the KEE system has been used to model product features as shown in Figure (4). There are two root classes the first one is the product features and the various *product.features* can be categorized as: *form. features*, *material.features* and *precision.features*. The second one is the facility features, and the various facility features can be categorized as: *cutting.tool.features*, *machine.features*, *fixture.features*, and *material.handling.features*, as shown in Figure (5).

Product Features

Form Features

Form.Features are presented as a subclass of the *product.features*; and can be classified broadly into two subclasses: *compound* and *primitive.features* (see Fig.4). *Compound.features* are broadly divided into two units: *external* and *internal.features*. *External.feature* can be further classified into subclasses such as *drafts, fillets, and rounds*. Each unit has a slot which contains various information about the unit characteristics such as *depth, length, and radius, etc*.

Feature Recognition From a Solid Modeller

Most solid modellers available today represent part geometry in terms of low-level geometric and topological entities such as surfaces, edges, faces, loops and points. Therefore, these modellers do not provide higher level abstractions of the part that relate directly to certain design functionalities or manufacturing characteristics. Research reported in this paper outlines an approach to provide this desired higher level abstraction. The approach adopted indicates that a design can be automatically evaluated for manufacturability during the iterative design process. By incorporating a geometric feature recognition technique into the CAD software, machining concerns can be evaluated as the designers builds the part. This approach is useful for several applications. First, the generated features database allows a reasoning system to perform tasks such as, design verification, manufacturability analysis and heuristic design optimization. And secondly, features can be used to facilitate NC machine programming, process planning and cost estimation.

The Interface to the Solid Modeller

To enable the construction of an interactive design process, the modeller used must provide sufficient external interface capabilities to allow both the modeller and an external program to be able to act together in a unified manner. Pro/Develop, the programmatic interface of the Pro/Engineer database in addition to bespoke software written for C and Unix environment, have been implemented to develop this system. The developed system provides the following facilities; (i) direct access to the solid modelling system database to perform unique and specialized engineering applications; (ii) direct access to the database to derive automated feature recognition. This technique contains an interface (UDF_Features Menu) which enables users to interact with the system easily and efficiently. It also enable designers to create form features such as, holes, slots, rounds, fillets, and drafts, as shown in Figure (2). In addition to the capability of identifying the features topologically and geometrically.

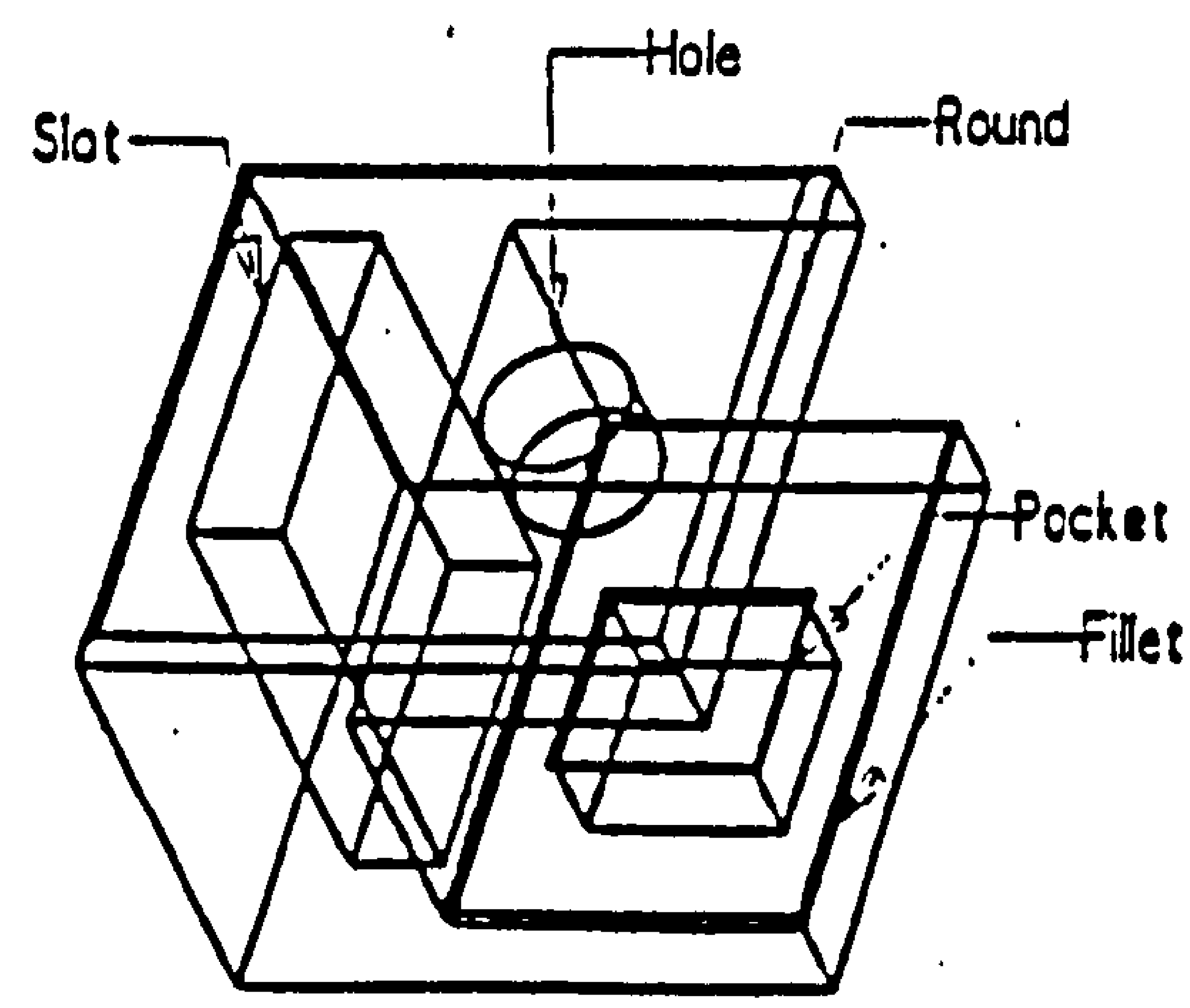

Fig.(2) An Object and its Form Features

The Communication Interface Between the Solid Modeller and the Reasoning System (KEE)

The KBS tool (KEE) together with the CAD system (Pro/Engineer) were seen as an ideal medium for achieving the goals of this research. Consequently, the integration between the solid modeller and the reasoning system was considered as a crucial step towards achieving the target of this project. KEE itself does not provide an external communication capability but allows complete access to Lucid's Common Lisp language. Common Lisp in turn supports a foreign language interface to communicate with PASCAL, FORTRAN, and C languages. These external languages can then open, read, *Primitive.Features* are divided into two subclasses: *concentric* and *non-concentric.features*. *Concentric.features* are rotational features whose axis of rotation coincides with the primary axis of rotation of the part. Non-concentric.features are rotational features whose primary axes of rotation are different from, and non-coincidental with the primary axis of rotation of the part. Further extensions to the form feature hierarchy can be done in the future to distinguish between the type of primitive features that make up a compound feature.

Material Features

The material composition, grade, and properties of a part are specified by the

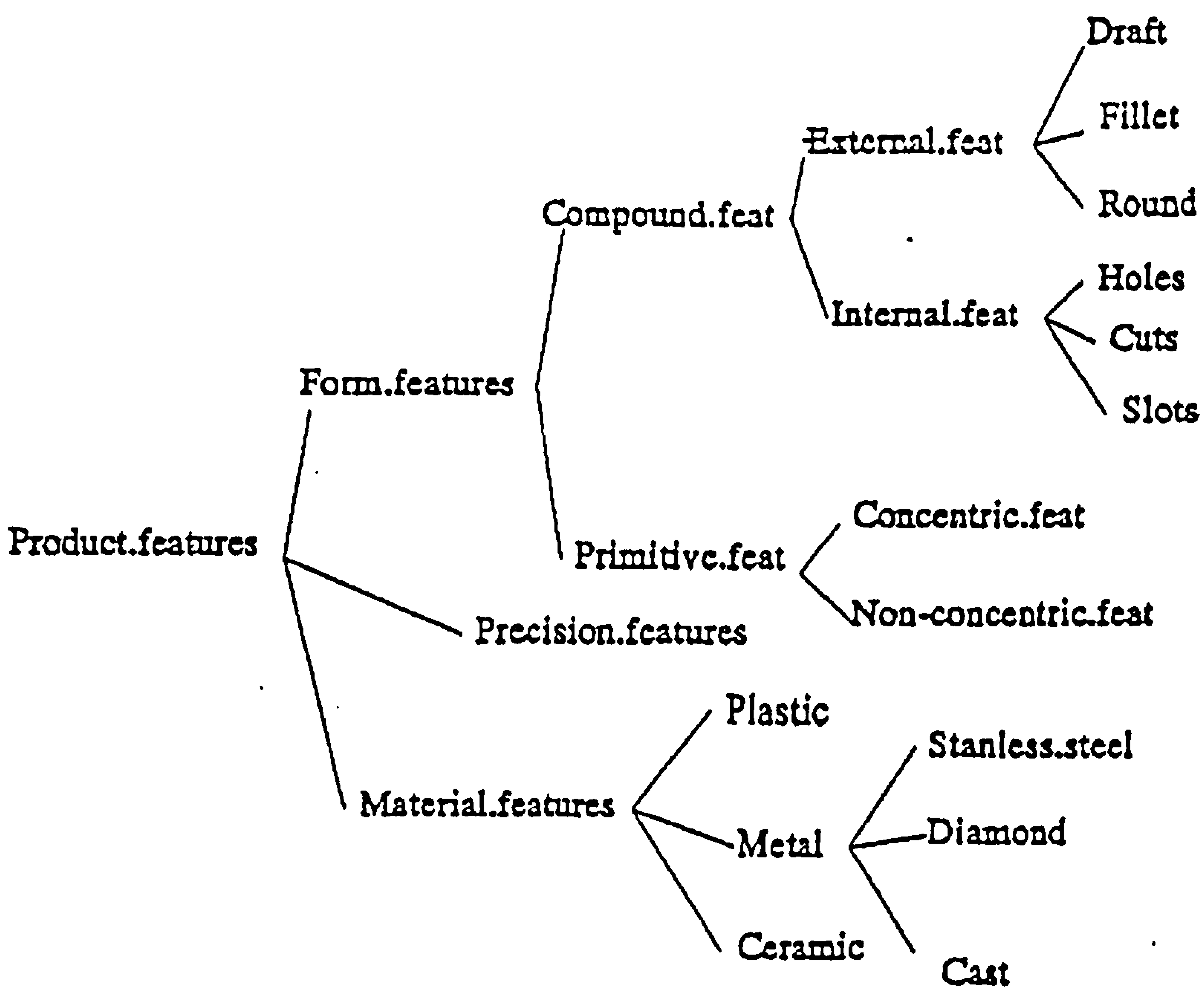

Fig.(4) Product Features Inheritance Hierarchy.

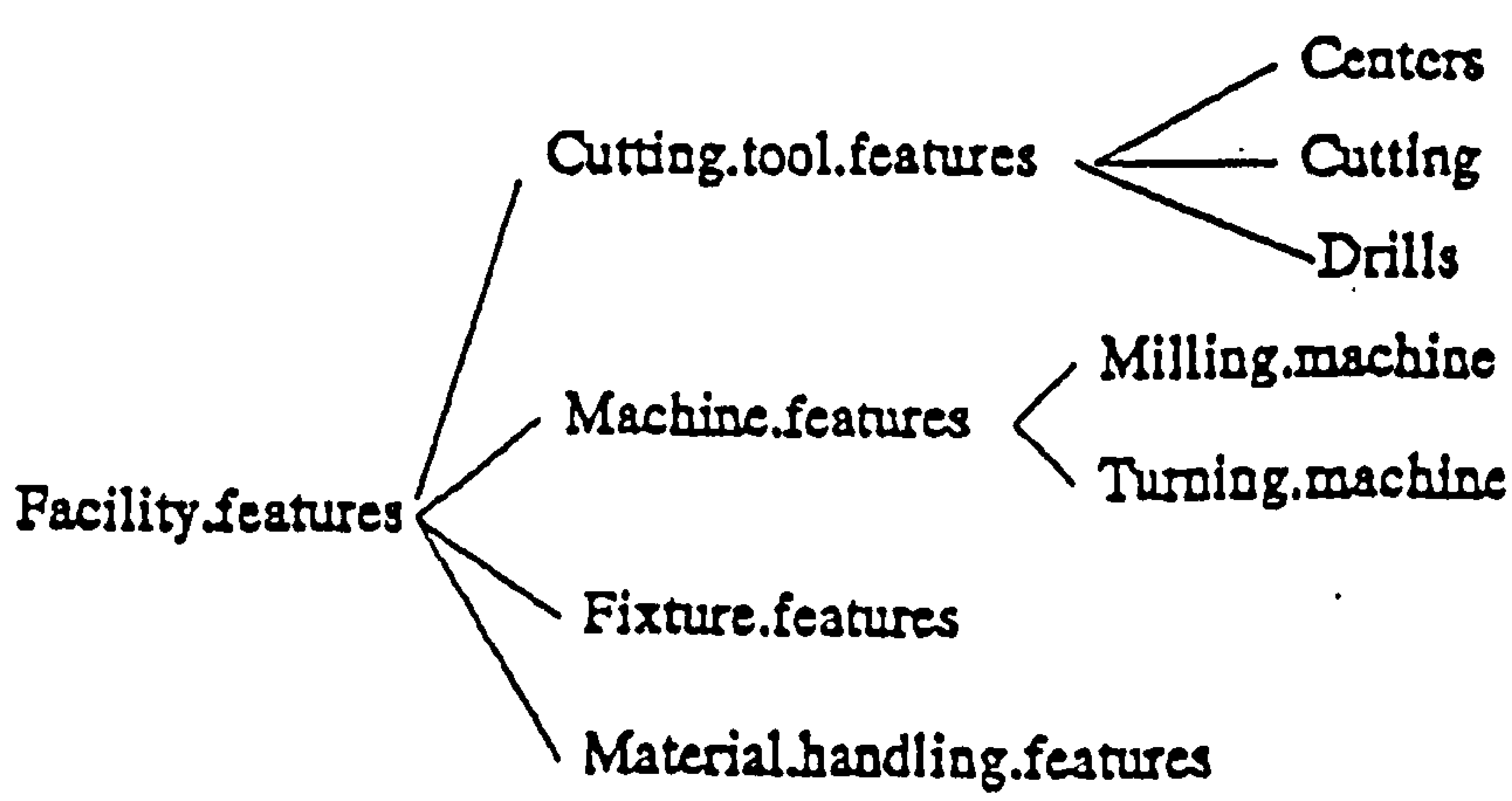

Fig.(5) Manufacturing Facility Inheritance Hierarchy.

material.features hierarchy. The portion of the inheritance hierarchy rooted under *Material.features* is shown in Figure (4). The material characteristics of a part are specified by indicating the appropriate material from this class of features.

Manufacturing Facility Feature Inheritance Hierarchy

The inheritance hierarchy underlying the frame based system used to model manufacturing facility features is shown in Figure (5). The root class is *facility.features* and the various facility features can be categorized as: *cutting.tool.features, machine.features, fixture.features, and material.handling.features.*

Machine.features and material.handling.features are used to characterize the various machines and material handling equipment available in a facility. The attributes of machine features describe the various types of machines available in the manufacturing cell such as, Milling Machines, Turning Machines, etc.

Fixture.features are used to describe the structural and functional characteristics of various fixtures and fixtures components used in the manufacturing cell. *Cutting.tool.features* are used to describe the structural and functional characteristics of various cutting tools and cutting tool components.

Machining Cost Estimation Procedure

This section describes the development of an approach for estimating the cost of a machined part or component early in the design phase of a product. Equations proposed in [12] have been developed to be more accurate and faster for determining machining costs, operation times, and production rates. The developed equations have been used for calculating the machining cost for the following processes: turning, drilling or reaming, tapping, centre drilling or chamfering and handling/setup. Generally, They can apply to both conventional and numerical control machine tools.

Determining Optimum Cutting Conditions

It has been known that the cutting speed forms a major component of the machining cost. In order to achieve the optimum cutting conditions, it is necessary to determine the mathematical relationship between tool life and pertinent cutting parameters such as speed, feed, and depth of cut. Probably the most common approach is Taylor's equation relating tool life to cutting speed this applies:

for turning

$$VT^n = S$$

for drilling, and tapping

$$VTt^n = St$$

With these Taylor equations, the cost for the various machining operations can be minimized. This has been done by substituting the appropriate Taylor equation into the cost equation, differentiating the cost with respect to cutting speed, and setting the derivative equal to zero.

The proposed system of equations [12] have been programmed in a common Lisp language and user interface has been setup to enable users to interact with the system easily. The interface has been carried out using the KEE function facilities and designed to enable users to get information about not only the total cost but also the individual cost elements such as turning cost, milling cost, drilling or reaming cost, tapping cost, centre drilling cost and setup cost as shown in Figure (6). Therefore, the user will be able to analyze and separate the significant from the trivial cost factors.

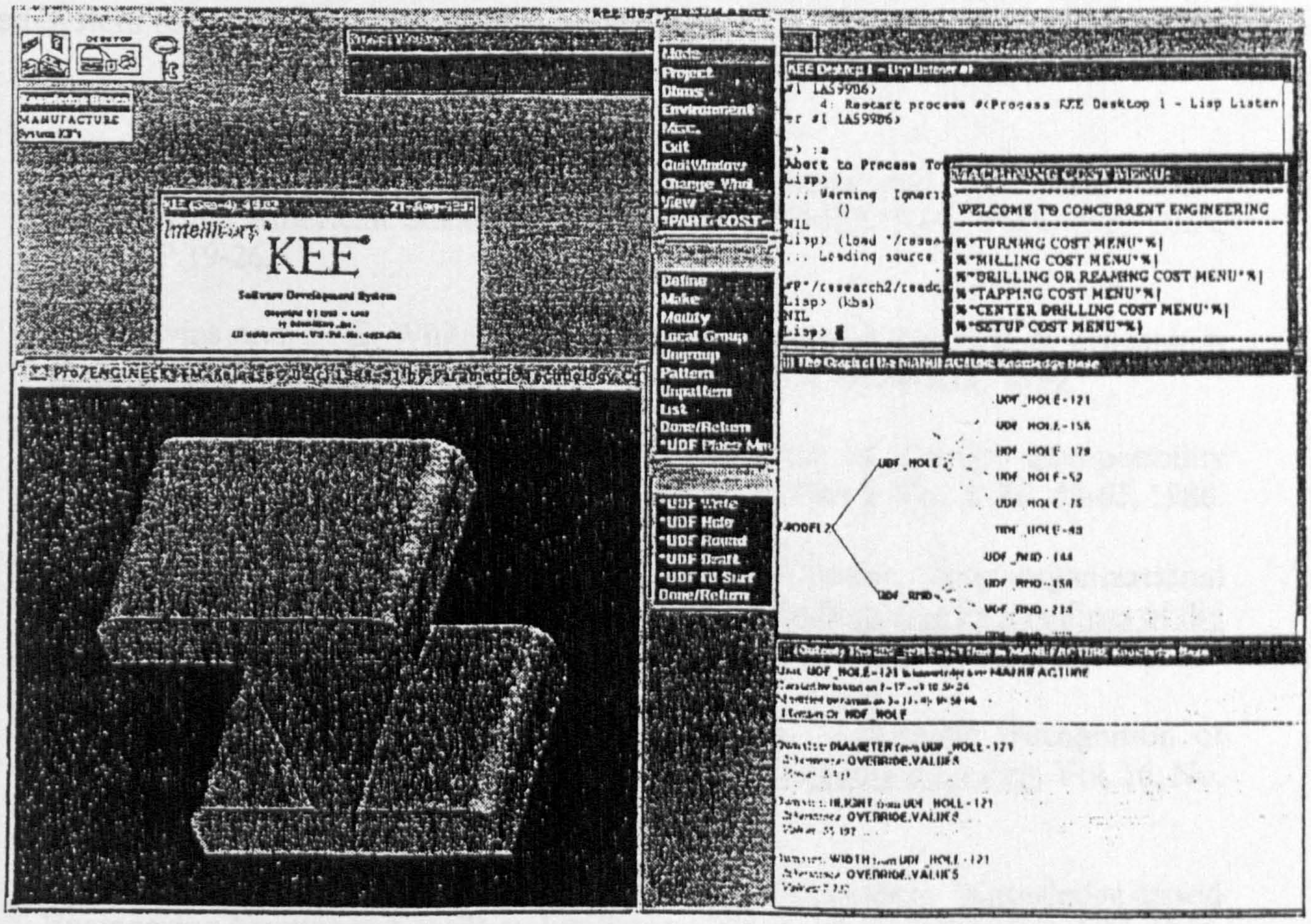

Figure (6) The Complete Integration of Pro/Engineer and KEE.

Nomenclature

CAD	Computer-aided Design.
CAE	Computer-aided Engineering.
CAM	Computer-aided Manufacturing.
NC	Numerical Control
DFM	Design for Manufacturability.
KBS	Knowledge-based System.
KEE	Knowledge Engineering Environment.
SE	Simultaneous Engineering.
V	Cutting speed.
T & Tt	Tool life.
S & St	Reference cutting speed.
n	Tool life exponent.

Conclusions and Recommendations

In this paper we have demonstrated a new methodology to integrate a Knowledge based reasoning System with a Solid Modeller for design analysis and machining cost estimation. The developed technique enables engineers to minimize the machining cost and improve the quality of the product. This work has been seen as an essential task towards achieving the concept of design for manufacturability/Concurrent Engineering.

Further work is required in this area to enhance the capability of the Knowledge-based System for other applications such as, Process planning, design for assembly, etc.

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